AMATEUR
TELESCOPE MAKING

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ALBERT G. INGALLS, Editor
Associate Editor, Scientific American

With contributions by

RUSSELL W. PORTER
Associate in Optics, The California Institute of Technology

REV. WILLIAM F. A. ELLISON, F.R.A.S.
Director of Armagh Observatory

GEORGE ELLERY HALE, Sc.D.
Honorary Director, Mt. Wilson Observatory

PROF. CHARLES S. HASTINGS, Ph.D.
Professor Emeritus of Physics, Yale University

JOHN M. PIERCE
Director of Vocational Training,
Springfield, Vt., High School

A. W. EVEREST

JOHN H. HINDLE, F.R.A.S.
Vice-president of the Manchester Astronomical Society

REV. HAROLD NELSON CUTLER

FRANKLIN B. WRIGHT, M.S.

ALAN R. KIRKHAM

F. J. SELLERS, F.R.A.S.

R. N. AND M. W. MAYALL

AND BY THE EDITOR

With a Foreword by

DR. HARLOW SHAPLEY
Director, Harvard College Observatory

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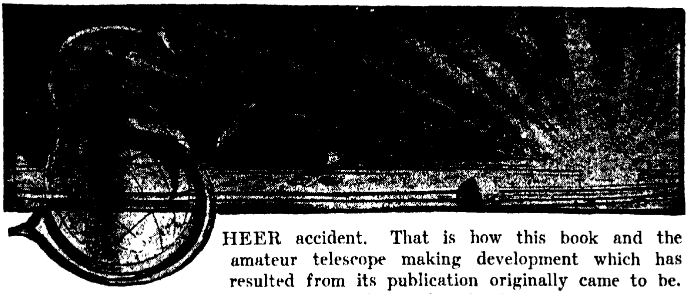
3 A. M. AND STILL AT IT

Here Porter, the artist, depicts the enthusiast as utterly absorbed in the most exacting and interesting part of the work —parabolizing the mirror. The cellar is the best place to work because its temperature is fairly uniform.

HOW IT CAME ABOUT



HEER accident. That is how this book and the amateur telescope making development which has resulted from its publication originally came to be. If you are bitten by the bug of the amateur telescope making hobby, you may pretty nearly blame the fortuitous fumbling of one man's thumb. Thus closely are things that are worth while in life linked up with the most trifling circumstances. Some years ago the editor of this volume, while in a public library, was half-consciously thumbing over a bound volume of *Popular Astronomy,* and by merest chance caught sight of the intriguing words "The Poor Man's Telescope." These words, it proved, formed the title of an arresting article (Nov. 1921) by Russell W. Porter, which told how the author made the concave mirror for his own reflecting telescope. A second article (Mar. 1923) related how a group of Vermont villagers under the same writer's instruction made their own telescopes and became amateur astronomers. The "poor man's" telescope, it was set forth, was not the more familiar refracting kind but the reflector. It was called the poor man's telescope because even a poor man, if he did not begrudge hard labor, might possess one by making it himself.

After reading these articles, an attempt was made at once to find detailed treatises on telescope making and, since the book resources of the whole vast New York Public Library were immediately at hand, it was fully anticipated that an armful of works on that art in the English language would be found readily available. Now it is a rare thing in these days of plentiful books concerning everything under the sun, when one cannot easily lay hands on at least a dozen works about even an obscure subject; generally, in fact, one's first task is to eliminate all but the best of the lot. Nevertheless, it turned out that in the whole English-speaking world there was only one book on telescope making for the amateur, and even that was not available in American book stores. This was "The Amateur's Telescope," by the Rev. William F. A. Ellison, Director of Armagh Observatory in Northern Ireland and a veteran maker of telescope mirrors. A copy of that book was obtained from London and it proved to be a gold mine. With its aid work was started on a modest mirror of six-inch diameter.

At this juncture Russell W. Porter, author of the articles on the poor man's telescope, was personally discovered and proved willing to lend ready ear to certain frantic appeals for practical advice, and in course of time the mirror was completed and installed in a most unpretentious mounting of wood.

Then a larger idea took shape. Why not, with the book by the Rev. Ellison and the immediate assistance of Russell W. Porter, and with the Scientific American as a ready medium of access to large numbers of scientifically-minded persons, attempt to popularize amateur telescope making as a widespread hobby? Would it make appeal? Would it? No one knew. To test the potential "reader interest," if any, in the subject, an article was published in that magazine (Nov. 1925), describing a night spent with the group of Vermont amateurs which Mr. Porter had fostered, at their star-gazing mountain-top clubhouse-observatory near the village of Springfield. In response, 368 of the readers of that article wrote to the editor of the Scientific American urging the publication of practical instructions for making telescopes such as the Vermont amateurs had made and used.

This looked like an auspicious beginning for so specialized a hobby, and Mr. Porter was accordingly invited to prepare two such articles. These two articles (Jan. and Feb., 1926), brief and inadequate as any mere article or two on such a subject must necessarily be, aroused so much interest that the publication of a book of instructions, more detailed in nature, was at once decided upon and a request for the right to reprint "The Amateur's Telescope" in America was cabled to the Rev. Ellison in Northern Ireland. This book, or most of it, and the two Scientific American articles by Porter were combined with other matter to make a modest volume of 102 pages, the first thin edition of the present work.

As time went on, the telescope-making hobby enlisted the interest and keen enthusiasm, sometimes almost fanatical, of more and more of the readers of the Scientific American. Descriptions of telescopes actually made were published in every issue of the magazine after 1926, and clubs of amateur telescope makers and astronomers (see page 486) were formed in the larger communities. Through correspondence and travel their members became mutually acquainted and, all over the nation and, indeed, all over the world wherever the Scientific American circulated—in the mountains of Java, in South Africa, the Argentine, Australia and New Zealand, India, Japan, Canada and elsewhere—amateurs interested in science and refined mechanics found themselves engaged in rubbing one piece of glass on another to make a telescope mirror and, as soon as this was completed, eagerly starting larger and larger ones. The first edition, some 8400 copies, of the little 102-page book was gone by 1928. A second edition, enlarged to 285 pages by the addition of new matter, was prepared that year, and the 5400 copies of that edition had vanished by 1932. The present edition contains the same matter, with trifling alterations and deletions, and with some 200 pages added.

Still the hobby goes marching on. Thousands of telescopes have been labored over by eager workers young and old, skilled and less skilled, men and women (several of these), "poor" men and rich men too. Telescope

making is a scientific hobby and it appeals doubtless because it exacts intelligence; requires patience and sometimes dogged persistence in order to whip the knotty but fascinating problems which arise; demands hard work—is not dead easy; and compels the exercise of a fair amount of handiness—enough to exclude the born bungler but no more than is possessed by the average man who can "tinker" his car or the household plumbing, or dissect and wreck a watch. Some use of the brain is also called for, but one need not be an Einstein. The hobby also appeals because the worker derives something of a thrill while shaping the refined curve of the glass as he realizes that, with scarcely any special tools but chiefly with the aid of an elementary test which greatly magnifies minute irregularities on the curve, he is able to work to within almost a millionth of an inch of absolute perfection. Finally, it may legitimately make appeal because the end-product, the telescope, is not only a tangible evidence, visible to all, of the worker's possession of the several virtues cited above, but is a valuable scientific instrument which places him on the threshold of astronomy and astrophysics, perhaps the most romantic branch of modern science.

The reader doubtless will discover that this book is a mine of practical information but that the same information is not arranged in a single sequence—he must mine it out. This is because the various parts were written by many different authors and at different times. Like Topsy, the book "just grew" or, as is sometimes said of the British Empire, it is "a fortuitous, unsystematized agglomeration of ill-assorted entities acquired at different times by opportunism and otherwise." However, like that very practical commonwealth, it works—thousands who have used it can testify to that. To organize its contents thoroughly, so that the reader might march straight through a logical sequence without jumping about, would require that it be rewritten entirely and by a single writer. But then it would lose most of its claim to authoritativeness, simply because it would thereby lose most of its numerous contributing authorities; one cannot eat one's pie and have it too. So the diligent worker will be forced to make the best of this disability, reading the volume twice or more while he works, and using the index to correlate cognate phases of the work.

It is suggested that the beginner read the first two chapters of Part I as an introduction or preview; then skip to Part II, where he will find the main detailed instructions for making his mirror. He should pause over Part III for a double reading, with strong emphasis on rigidity in design. If he wishes, he may attempt to fish assistance and sundry sidelights from the Miscellany at the back, skipping the harder notes which, with the remaining parts of the book, are for more advanced workers.

Unless you are sure you are a genius, do not succumb to the natural temptation to make a large telescope at the very start; there is plenty of grief to be had at first in a small six-inch glass, and the experience gained on this size will be invaluable on a larger one. If, however, you should essay a 12-inch glass at the outset, as a few have done, you no doubt will succeed in the end. It will, however, prove actually possible in the average case to make a series of, say, three mirrors—a 6-inch, an 8-inch *and* a

12-inch—in less time and with less trouble than is required to make a single 12-inch mirror without the valuable experience gained on smaller and less difficult sizes. It will also prove to be more fun. The usual experience is this: At the start the beginner thinks mainly of acquiring the end-product, the telescope, and regards its construction merely as a task. Later he often discovers that more fun is to be had in making than in actually using it. Don't deprive yourself of this fun by making your last telescope first.

No detailed dimensioned drawings and specifications are given in this book, but the basic principles common to all telescope mountings are explained in Part I, Chapter II, also in Part III, which especially stresses rigidity. Instead of slavishly following someone else's specifications, the resourceful worker will wish to concoct his own mounting, and then it will be uniquely his, expressing his own individuality. This adventure affords half of the fun and satisfaction of the game. It is not, however, unsportsmanlike to study closely the details of telescopes already made by others and to "lift" this or that feature from them, provided one improves upon these features. To that end many photographs of telescopes made by readers of the earlier editions of this book and published, meanwhile, in the Scientific American, have been inserted here and there in this edition.

Some of the workers—a very few—have strongly urged that the amateur's telescopes be standardized on a few definite type specifications, arguing that this would save labor. Others believe that standardized hobbies connote standardized people with standardized ideas, and that the introduction of mass production and labor-saving ideas of efficiency in connection with a hobby is comparable to hiring a workman to play one's games for him. A hobby should be a way to waste time, not to count it.

In his introductory chapter (Part II) Ellison says that in telescope making "the amateur has shown the way to the professional, and forced the pace for him, ever since Herschel's time." Since 1926 when the telescope making hobby was imported from Great Britain, where its antecedents were already ancient, there have been fresh signs which seem to point in the same direction. For example, formerly inexperienced amateurs whose interest in telescope making was first enlisted by earlier editions of the present book now contribute to its pages (Parts IV and X). The former student has become the teacher. This trend will no doubt go on, and we shall be surprised if the next few years do not bring to light at least one Ritchey who perhaps began by making a modest little six-inch telescope with the aid of "Amateur Telescope Making." Many amateurs are already doing work equal to professional grade.

ALBERT G. INGALLS,
Associate Editor, *Scientific American.*

New York, November, 1932.

The present (4th) edition contains new sections on mountings (p. 130), HCF laps (p. 149), drives (p. 154) machine polishing (p. 234), sidereal time (p. 337), replacing older sections; also some new notes and corrections.

—A. G. I., Sept., 1935.

FOREWORD

By Harlow Shapley, Ph.D., Director, Harvard College Observatory

"I set myself to work", wrote the great Christian Huygens, one of the earliest of amateur telescope makers, who, inspired by Galileo's telescopic revelations, proceeded to reveal celestial marvels on his own account, and in 1659 unravelled the secret of Saturn's rings—"I set myself to work with all the earnestness and seriousness I could command to learn the art by which glasses are fashioned for these uses, and I did not regret having put my own hand to the task".

"And now that I, too, have fashioned some glasses," the amateur instrument maker may inquire, "what next?"

Three things are next; the first is inevitable, the first two are natural, and all three are possible. The first is to feel satisfaction that you have created something with your own hands. The second is to indulge your curiosity, and incite that of your friends, by using your equipment on the objects for which it is designed; but, in so doing, keep in mind that pride of manufacture is justifiable, but that humility and wonder are the appropriate attitudes in contemplating the stars.

The third privilege of the amateur, who has followed the book and his own intuition in constructing astronomical tools, is to use his product advantageously for science. To do so effectively, he must be sincere and have both freedom and spirit. Assuming that you who read this are so gifted, I shall make some suggestions.

First, if you have "fashioned some glasses" into a telescope of three inches aperture or larger, you can do valuable work on variable stars. The American Association of Variable Star Observers would welcome you to its international membership, give you instructions, charts and encouragement. And if you are of the right stuff, within a few months you should become, in your extra evening hours, one of the contributors toward the solution of some major astronomical problems, such as the nature of stellar variability and the evolution of stars.

If the Earth and the Moon attract you more than the remote telescopic stars, and if you have access to accurate time by observatory clock or radio, you are invited to learn the simple technique of occultations—that is, the accurate timing of the eclipsing of stars by the Moon. It is only of late that we have come to realize the important work that the serious amateur astronomer can do in helping to determine the Moon's position by observing the predicted occultations. Your observations will be directed and studied by professionals; and you will be aiding in a fundamental research—the measurement of irregularities in the rotation of the Earth and the lengthening of the terrestrial day.

Second, if you have fashioned (or bought) and mounted a very rapid photographic lens, in which the ratio of focal length to aperture is 3.0, or 2.0, or even less, you are invited to join the select ranks of astronomical sportsmen and go gunning for photographs of shooting stars. Photographing the

shooting stars costs no more than trout fishing in the Adirondacks, or hunting mountain sheep in the Rockies, or angling off Catalina Island; but it should have much the same appeal and difficulty, and a greater thrill when success arrives. It is not hard to see shooting stars and make unreliable visual observations of them; but it is an art, mastered by few amateurs or professionals, to photograph the elusive intruders in our upper atmosphere and thereby make permanent and accurate records. We must have more meteor photographs. One hundred thousand plates in the Harvard collection have been examined, and have revealed only a few hundred meteor trails. They form the most important collection of such data in the world, and the importance lies largely in the fact that astronomers now see the great significance of meteors in the problems of interstellar space, of comets, and asteroids, of the nature of nebulae, and of the origin and maintenance of starlight. Meteors are fundamental and little known; they are the game of the astronomical sportsman, and if he can work with others of his kind, so much the more important his contribution.

Third, if you have fashioned some contrivance for the better recording of meteor paths observed visually among the stars, then you should get acquainted with the American Meteor Society, and the work it tries to do. You will find that there is good systematic work to be done in that field without camera and without telescope.

In summary, if you have the time and spirit for it, you can crown the zeal you have displayed in making an astronomical instrument by using it intelligently and constructively on important projects. If you communicate your earnest astronomical aspirations to any of the observatories, you will be freely counselled. The professional astronomer has gained too much from the amateur in the past to disregard him at this time, when many useful contributions can be made by the man whose hobby is astronomy. But remember that constructive work is only one of three privileges of the amateur telescope maker. The second may be the most important—to look into the heavens with uncovered head and humble heart.

AMATEUR TELESCOPE MAKING

Part I.

CHAPTER I.

Mirror Making for Reflecting Telescopes

By Russell W. Porter, M.S.
Associate in Optics, The California Institute of Technology

In the reflecting telescope, *the mirror's the thing.* No matter how elaborate and accurate the rest of the instrument, if it has a poor mirror, it is hopeless. Conversely, a good mirror, even if it is crudely and simply mounted, makes a powerful and efficient astronomical tool.

We are concerned in this chapter with the shaping of the telescope mirror.

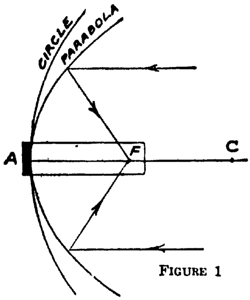


Figure 1

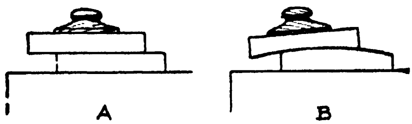


Figure 2

Figure 1. THEORY OF THE MIRROR. *Many find it difficult to understand why the focal length is only one-half of the radius or distance to the center of curvature, while in the shadow test the light is focused at the center of curvature. In the first case the rays are coming from a star, at almost infinite distance, and are therefore virtually parallel, while the rays that reach the mirror from the pinhole are divergent (radii). In this diagram, let us imagine we could grasp the two parallel rays indicated and actually pull their right-hand ends together until they touched the point C. As we drew them in, the angle at which they would now meet the mirror's surface would change, and since light is reflected away at the same angle at which it strikes a mirror, the reflected rays would shift at the same time from F to C, at double the distance of F.*

Figure 2. WHY THE CURVES DEVELOP. *The upper disk tends to hollow out because at the extremities of the strokes the abrasive effect on both disks is increased. This is due to the overhang and to the consequently increased pressure on the central portion of the upper disk, as well as the marginal part of the lower.*

This consists solely in giving one side of it a concave, polished surface. This surface is to be so very nearly spherical that we shall first attempt to make it precisely so; and at the very last we shall alter it to the kind of surface familiar to us all in automobile headlight reflectors, and known among the highbrows as a paraboloid of revolution.

Such an automobile headlight has the property of throwing out from a concentrated source of light placed at a focal point near it, a beam of parallel rays. (See Figure 1.) We shall, however, use this reflector the other way around, that is, by receiving parallel rays of light from a distant object (star); and by reflecting them from a properly curved mirror we shall bring them to a point or focus (F, Figure 1).

Our curve, however, is so small a portion of this widely sweeping parabola (the black area represents the mirror) that it is extremely shallow, and so it nearly coincides with the superimposed spherical curve. At first, therefore, we shall seek to hollow out a spherical curve, later deepening it very slightly into the paraboloid.

Since the angle of reflection of a beam of light is equal to the angle of incidence, the parallel, arriving rays will be reflected approximately to a focus whose length may be regarded as one-half of the radius of curvature, C-A, Figure 1.

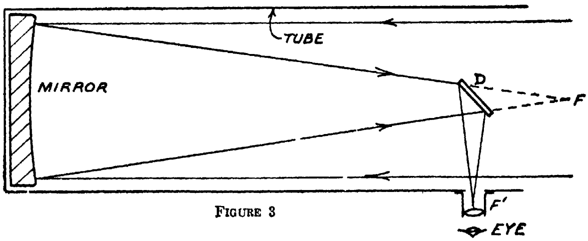


FIGURE 3

FIGURE 3. WHY A DIAGONAL IS NEEDED. *Without it the rays would theoretically come to a focus at F, where the observer's head would eclipse the light from the object. The diagonal mirror, or a prism, reflects them to F′.*

Enlarging the mirror of Figure 1, A, we have in Figure 3 the essentials of the Newtonian, reflecting telescope. Light from a distant object falls down the tube to the mirror, and normally would, by reflection, produce an image at the focus, F. The converging rays are, however, intercepted at D by a small diagonal mirror or prism that delivers them to a lens called an eye-piece at the side of the tube, where the image is examined.

I will take as our standard, a mirror six inches in diameter, having a four-foot focal length. The beginner is not advised to essay a larger mirror for his first effort, since his difficulties will be found to multiply quite disproportionately as the diameter increases. If two flat glass disks (A, Figure 2) are ground together, one over the other, with an abrasive between, lo and behold!—the upper one becomes concave, the lower one convex. This is because the pressure per unit area, and therefore the amount of abrasion, is increased on the central portions of the upper disk and outer portions of the lower one when the upper disk overhangs as in *B*.

A straight, back-and-forth stroke, in which a given point on the upper disk moves across one-third the diameter of the lower, has the property

of holding the two surfaces spherical. This is due to the fact that sphèrical surfaces are the only ones which remain in continuous contact at every point when moved over each other in any direction. This fact is a veritable godsend to the amateur—and to the professional, too, for that matter—for he may go confidently forward through the different stages of grinding and

FIGURE 4

PREPARING THE PITCH LAP

Melted pitch is being poured on the convex, upper face of the tool. Note the temporary collar of wet paper, which acts as a retaining wall for the pitch until it cools. Tool and mirror should previously have been placed in luke warm *water. If pitch is poured on a cold tool it will "set" so rapidly that there will be little time to make it conform to the curve of the mirror. But if the two disks are somewhat warm, there will be about ten minutes time in which to make a lap that will preserve good contact. Thus the worker may "take it easy" and do it correctly. Keep cold drafts away from the job. Warm water striking cold glass is not likely to break it, but cold water striking warm glass may.*

polishing with the knowledge that his mirror will come out nearly as it will be when it is finally deepened into a paraboloid.

The depth of the curve increases with grinding, and it is gaged with a template of the proper radius. Since by our rule, the radius, A-C, Figure 1, of the curve of the glass is twice its focal length A-F, a template is made from tin, with a radius of twice 48 inches, or 96 inches. Therefore a stick

of wood (not a string, which would be elastic) should be tacked to the floor at one end so as to pivot, and a knife point held at the opposite end, or a sharpened nail driven through at the proper distance, should be used to scratch the desired curve to which the tin should be cut. For our six-inch mirror the hollow will come to about .05 inch deep.

The lower disk of glass is fastened to a pedestal or to a weighted barrel so that one can walk around it in grinding, or it may be held be-

FIGURE 5

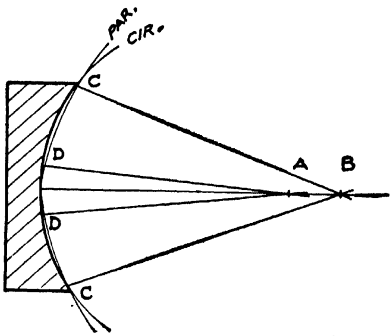
CUTTING CHANNELS IN THE PITCH LAP

Use a flexible straight-edge and a sharp knife. Keep everything wet, to minimize sticking of the pitch. In spacing the channels, precision serves no particular purpose. Do not center them, in any case. After the lap is formed and the channels are cut, leave the mirror on the lap until the tool, pitch and mirror have regained uniform room temperature. It should then be "cold pressed," or weighted, to insure the establishment of an even contact, which may have been disturbed during the cooling process.

tween one removable and two fixed buttons on the corner of a stout bench or table. (See frontispiece.) Using melted pitch, a round handle is attached to the upper disk, which is first heated slowly in water to a slightly unpleasant warmth for the hand, taking care that no cold water drops fall on the warmed disk, for they might break it.

The grinding is done by placing wet carborundum grains of successively

finer sizes between the two disks, care being taken after each size is used to wash all parts of the work entirely free of the larger sized grains, which would otherwise scratch the disk. The strokes are straight forward and back, the center of one disk crossing that of the other. The glass also rotates bit by bit in the hands, in order to present a new direction for each stroke; and from time to time, in order to prevent the wearing of the glass unsymmetrically, the worker shifts positions around the pedestal; or, if working on a bench, he turns the lower disk, called the "tool" (we shall discard this tool at the end) to a new position.



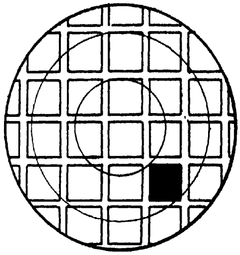


FIGURE 6

HOW MUCH HAVE WE PARABOLIZED?

The radius of a parabola shortens as its vertex is approached. Therefore the zone of the parabola near the edge, C, C, may be regarded (in practice) as part of a sphere with radius C-B. The central zone is regarded as part of a smaller sphere (shorter radius) with radius D-A. In the shadow test we can actually measure the distance A-B with a scale, and from this we can work out the amount that we have deepened or parabolized the center of our spherical mirror.

A TYPICAL PITCH LAP FOR A SIX-INCH MIRROR

The black square represents a facet removed from the lap in an effort to treat a depressed zone. Thus there would be less abrasion over the path traveled by this region as the mirror was rotated in polishing, and a zone (see rings on drawing) would tend to be raised above the general level of the glass.

Each grade of abrasive is used long enough to remove the coarser pits by the preceding grade, and it will save much time and labor in the polishing if a small quantity of washed 6F ("sixty minute") emery is used after the Number 600 carborundum.

All the preceding work is covered in great detail by Ellison in "The Amateur's Telescope," Part II of the present book, which at this time is the only modern work of this nature available in America.

The bench and both disks are now thoroughly washed in order to remove all traces of grit, preparatory to polishing.

Pitch is melted over a stove. It is tempered by adding (not over the fire) sufficient turpentine until a cooled sample placed between the teeth

will just "give" slowly without crumbling, or will show a slight indentation of the thumb-nail under moderate pressure. The pitch is poured (Figure 4) over the tool, which has been warmed in water, and dried, and when it is partly cool, the glass is wetted (in warm water) and pressed down on the pitch until perfect contact is obtained between glass and pitch. V-shaped channels an inch apart are now cut across the pitch at right angles to each other, to allow free access of the rouge and water to all parts of the glass. Do not center this system of channels or you may produce zones in the mirror. See Figure 6.

Rouge mixed with water is now substituted for the carborundum and the polishing is carried on to completion, using the same strokes as in grinding. The time thus far consumed in grinding should be about five hours; polishing may require nine hours, divided into "spells." Through all these operations Ellison goes with painstaking care, anticipating the pitfalls into

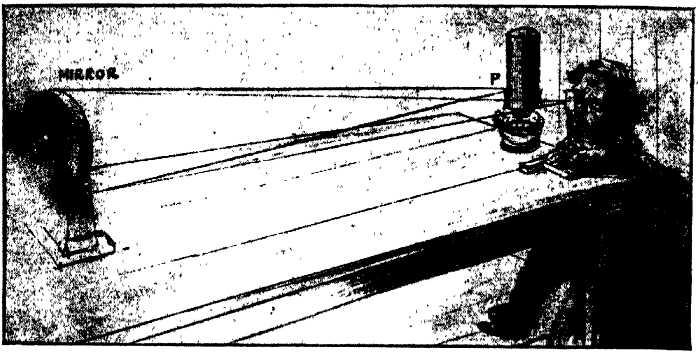


FIGURE 7

MAKING THE SHADOW TEST

The mirror does not necessarily have to rest on the same surface with the lamp and knife-edge, but all three should rest on stable supports which will not vibrate after the hand is removed from the knife-edge.

which the tyro inevitably falls. Were I to emphasize one caution over another, it would be the care required in preserving complete contact between the glass and the pitch lap surfaces while polishing.

If one-third strokes have been maintained in grinding and polishing, the surface of the glass will be nearly spherical. How shall we find out? The method I shall now describe is one of the most delicate and beautiful tests to be found in the realm of physics. By it, imperfections of a millionth of an inch on the glass can be detected, and all the tools required are a kerosene lamp and a safety razor blade! This method of testing mirrors, called the Foucault knife-edge test, was unknown until about 1850; before that time mirror makers were groping in the dark. Even the great Herschel

—father of the reflecting telescope—did not know when his mirrors were right, except by taking them out and trying them on a star.

If an artificial star made by a tiny pinhole (use a needle point) in a

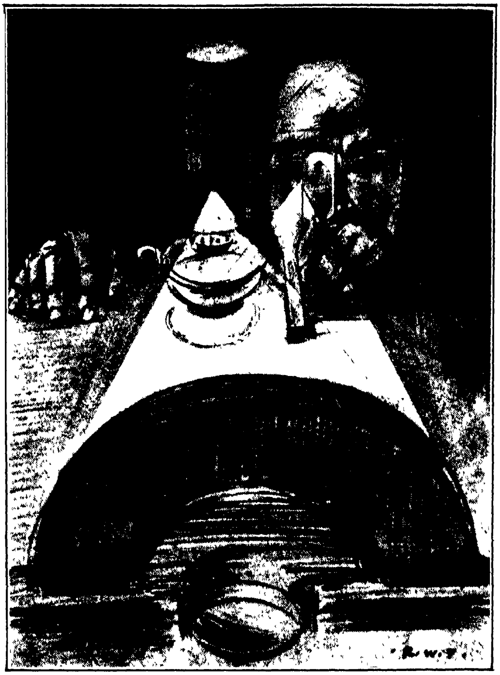


FIGURE 8

MAKING THE KNIFE-EDGE TEST

The semi-circle in the foreground is the back of the mirror, with its handle, set in a simple wooden frame-work which can be made of a packing box cut down. Beyond is the lamp with metal chimney pierced by a needle hole; also the knife-edge. The latter consists simply of a dulled safety-razor blade or any strip of metal set in a split stick of wood which is driven into a hole in a block of wood. This crude equipment serves as well as if it were elaborated with more complicated devices.

tin chimney on a kerosene lamp (an electric lamp will also be suitable) were placed at the center of the sphere of which the mirror's curve is a very small part, all of that portion of the light that emerges from the pinhole and strikes the mirror, is reflected back to the pinhole; for these light rays

are all radii of the sphere, and by reflection they must return as radii back to their source, the pinhole.

In practice, the pinhole is pushed over a little to the right of the center of curvature so that the cone of reflected light may clear the chimney and enter the eye, as shown in Figures 7, 8 and 9. The mirror is placed on its edge on some suitable support, at table height, in a fairly darkened room. The lamp and the knife-edge (mounted on a block of wood) are placed on a table as shown, and about eight feet from the mirror, viz., at its center of curvature. The lamp remains stationary.

At first, considerable difficulty may be encountered in picking up with the eye the reflected cone of light. One way is to replace the tin chimney with a glass one, walk away from the lamp, keeping it in line with the mirror, when the image of the lamp will be seen in the mirror itself. Then bring the eye forward slowly, keeping the lamp image in view, and move

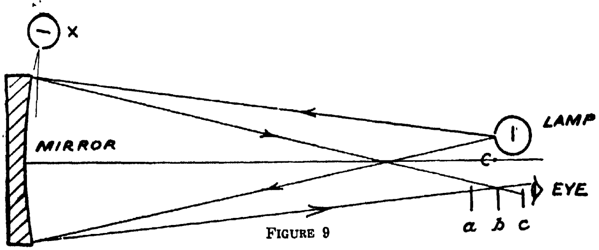


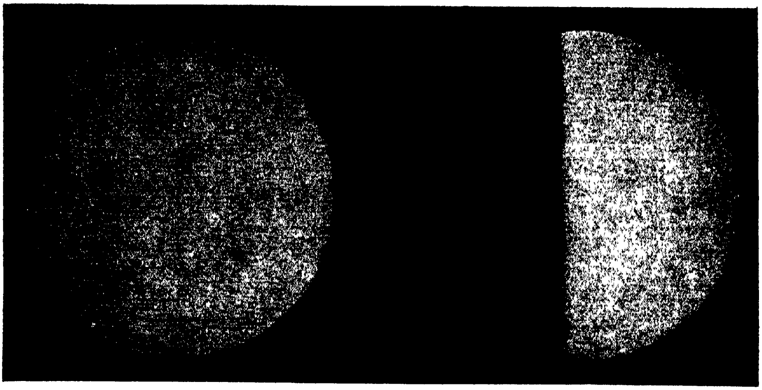
FIGURE 9

FINDING THE CENTER OF CURVATURE OF A SPHERICAL MIRROR

This is comparatively easy if the mirror is a true sphere. This point, b, can be located quite precisely. If, however, the mirror is parabolized, we speak of the "mean center of curvature," that is, half way between that of the outer zone, regarded locally as a section of a sphere, and the central zone, similarly regarded.

the knife-edge to the right until it cuts off half of the image. The tin chimney is then put on and the image of the pinhole may be picked up somewhere near the edge of the safety razor blade. As the eye approaches the position shown in the figures, this pinhole image begins to expand until a position is reached where the mirror is flooded with light over its entire surface—almost dazzling. See shadowgraph A, Figure 10. An alternate method is to use a piece of ground glass, which can be prepared by rubbing it with carborundum, to explore the neighborhood of the lamp, picking up the bright spot of light on it.

Now comes the remarkable knife-edge test. The razor blade is moved in from the left until it cuts into the reflected cone of rays. If at a, Figure 9, that is, *inside* of the center of curvature, a shadow will come in on the mirror from the left, as might be expected (shadowgraph B). If, however, it cuts the rays at c, Figure 9, that is, *outside* the center of curvature, the shadow will advance over the mirror from the right, giving appearance the reverse of shadowgraph B (or as B appears with the page turned upside down.) But *at* the center of curvature, b, the mirror, if spherical, darkens



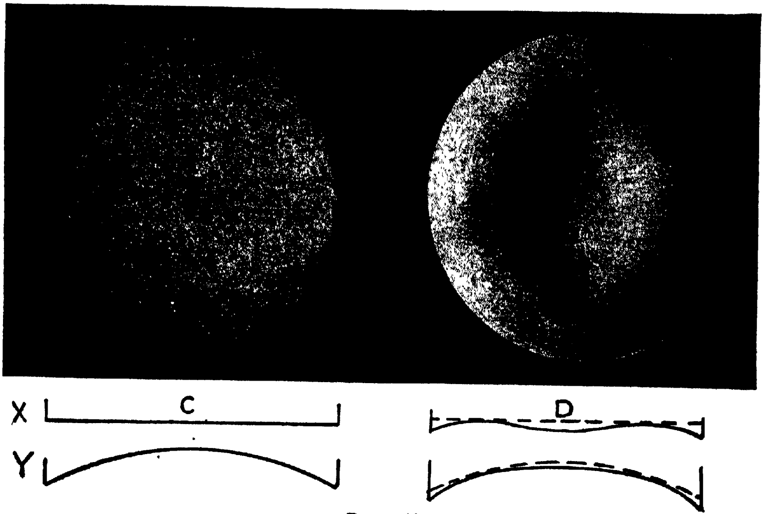
A

APPEARANCE OF MIRROR BEFORE THE KNIFE EDGE CUTS THE REFLECTED LIGHT.

B

KNIFE EDGE INSIDE THE CENTER OF CURVATURE OF THE MIRROR.

FIGURE 10



SPHERE

OBLATE SPHEROID

FIGURE 11

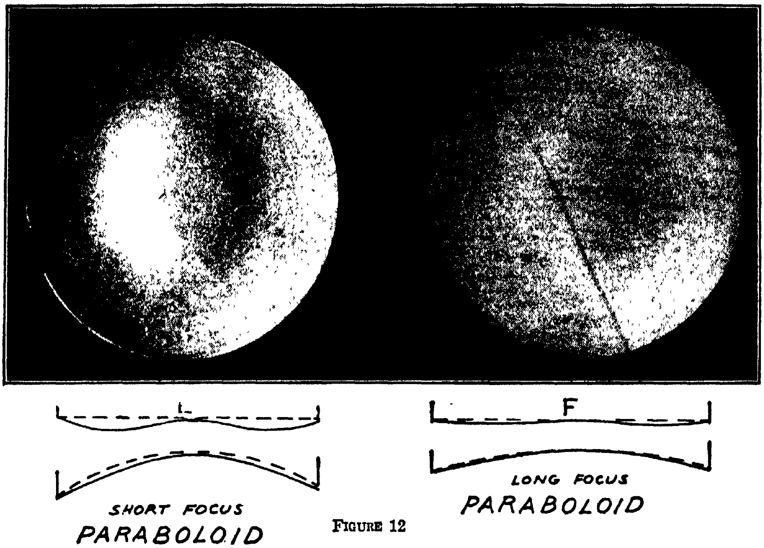


FIGURE 12

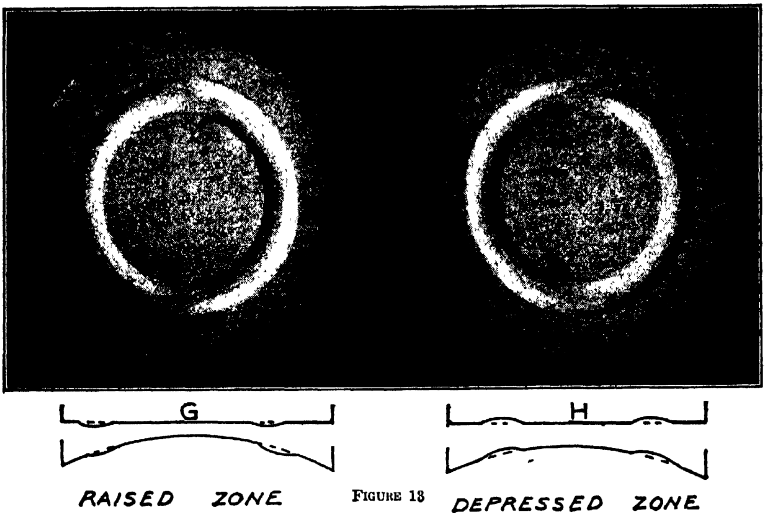


FIGURE 13

simultaneously over its entire surface, becoming evenly gray like shadowgraph C, Figure 11. As the knife-edge is moved farther, the shadow quickly vanishes. This is the simple test for a spherical surface, but it would be sheer luck if one's mirror appeared thus at the first test.

Viewed as just described, the surface of the curved mirror does not seem curved, but has the strange illusion of being flat. The observer *knows*

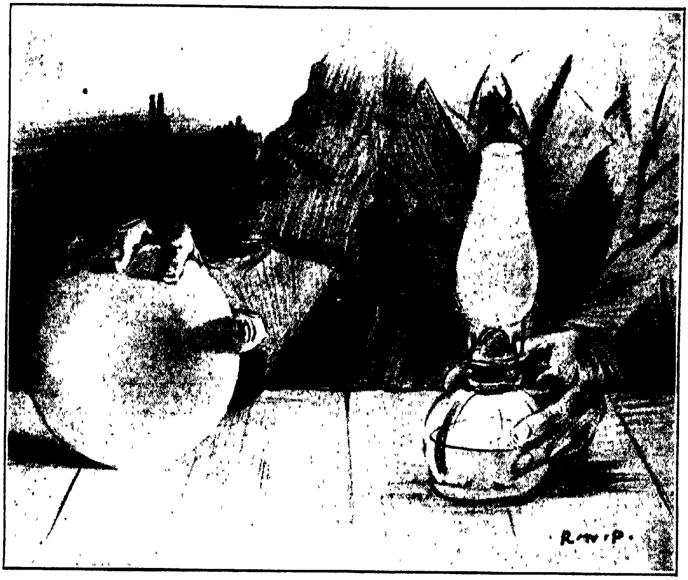


FIGURE 14

AN EFFORT TO EXPLAIN THE ILLUSION OF THE KNIFE-EDGE SHADOWS

The real source of light in the shadow test is the pinhole, which is in front of the mirror. But the mirror appears as though it were being illuminated from one side, grazingly, as in this sketch.

it actually has a section like Y, under shadowgraph C, but it *appears* flat, like apparent section X, same place.

The surface having been brought to a sufficiently fine polish and to a spherical curve, the remaining work on the mirror, known as the "figuring," consists in slightly deepening this spherical surface into a paraboloidal surface, and this is done by polishing away the center faster than the edge. The final goal is to make the mirror appear, when the razor blade is beginning to cut off the light, like the shadowgraph E, F, (Figure 12) or some intermediate depth, depending on the focal length, which need not be exact.

A common imperfection will be a raised or depressed zone, appearing like G and H, Figure 13, whose true (lower) and apparent (upper) sections are shown beneath them. In the case of the raised zone the shadow has all the reality of a flat surface on which is a raised portion in the shape of a ring, the left slopes of shadowgraph G, being in the shade, and the right slopes being in the light, *as though* the mirror were illuminated by a lamp placed on the opposite side of the glass from the knife-edge, as at X, in Figure 9. Figure 14 is an attempt to show how this imaginary lighting, at grazing incidence, *would* produce these shadows. Here the shadow of the man's fingers is superposed over the knife-edge shadow of a paraboloid. Conversely, a depressed zone (shadowgraph H) will have its lights and shades reversed.

Other characteristic shadowgraphs shown indicate curved surfaces well known to geometers under mouth-filling names. I would refrain from repeating them here for fear of throwing the novice into a panic of discouragement, but they must, nevertheless, be labeled for purposes of identification. Perhaps it will refresh the student's memory to note again the relations of these curves as shown in conic sections.

We have already considered the sphere whose section gives a circle (near top of cone, Figure 15). Its neighbors below are the ellipse, the parabola, whose plane lies parallel to one edge of the cone, and the hyperbola. When rotated (see discussion, p. 394) the ellipse produces a solid, the ellipsoid. This term, which is synonymous with prolate spheroid, when used in mirror making refers to the region of the vertex. The parabola, when detached from the cone and rotated, produces the paraboloid and *this is the surface of a perfect telescope mirror.* The hyperbola is steeper and on the other side of the parabola. The shadows of these three curves are all alike in shape and size, though they differ somewhat in depth, and therefore in order to distinguish them it is necessary to take measurements by means of the knife-edge. The same curves are not even alike in depth of shadow for all mirrors; a mirror of short focus gives a stronger shadow (shadowgraph E) and a mirror of long focus a fainter shadow (shadowgraph F). The oblate spheroid (shadowgraph D) comes from the side, not the vertex, of the ellipse.

There is something uncanny about these shadows and shadowgraphs. As before mentioned, they should all be interpreted *as though* illuminated by light coming in from the right. But if one can force one's self to imagine these shadows as produced by light coming from the left, they will give an impression exactly the obverse. For example, in the case of the zone (shadowgraph G), one can change its appearance from a bas-relief to an intaglio, like shadowgraph H, by imagining it lighted from the left; and with a little experience one can make it perform in either manner at will. The rule is to consider the light coming from a direction opposite to the knife-edge. Ellison is almost unique among mirror workers in placing the light on the left and the knife-edge on the right.

Now all of these possible surfaces into which one's mirror may develop, are to be treated in the same way—the apparently raised portions are worn down to an apparently flat surface. There are several ways of accomplishing

this result and all are described by Ellison in Part II, at greater length than the present space could possibly permit. In general, a zone may be reduced by removing a part of the pitch lap, for it is evident that a square of pitch removed as shown in Figure 6 would tend to raise a zone on the mirror. The danger here is in producing unexpected zones, and the drawback of having to remake the lap (always a fussy job) if the altered pitch fails to correct the glass. Suffice it to say that, as explained in Part II,

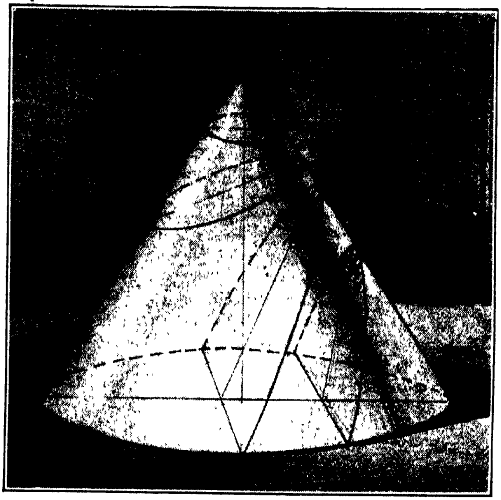


FIGURE 15

THE VARIOUS CONIC SECTIONS

The curves that may arise as the mirror is worked may be expressed as sections taken at various parts through a cone. For purposes of instruction an actual cone of wood may be cut across on each of these planes. It is well for the worker to become familiar with the nature of each type of curve or conic section. Any good encyclopedia describes them.

Chap. V, there are several strokes and positions of the glass overhanging the tool that will bring almost any surface to that of the desired sphere, ready for the slight deepening into a paraboloid, without changing the lap.

This is the hardest, but at the same time the most fascinating, part of mirror making. Any one of these surfaces is so close to the sphere that no mechanical means could detect a difference between them. And yet, under the knife-edge, each type stands out glaringly with its own characteristic shadow—never to be forgotten when once seen.

Let us now assume that the mirror has been brought spherical—that it appears flat, under test. The curve now to be sought belongs to type E, F (shadowgraphs). This is very close to the sphere—so close that but a few moments' polishing with a long stroke, or by letting the glass overhang the tool sidewise, will produce it. *Frequent testing is therefore essential during this crucial work of figuring the mirror.*

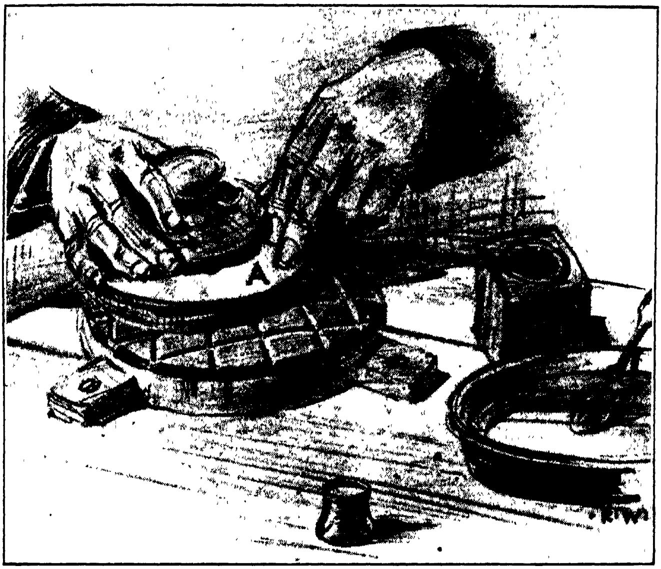


FIGURE 16

PARABOLIZING BY OVERHANG

The commonest of the several possible methods. Light side pressure is being exerted by the left hand. The method of permitting the hands to touch the glass, as depicted above, especially during the later stages of polishing and during the figuring, has been criticized. The warmth of the hands will not be so likely to expand the glass and affect the figure adversely if an easily removable annular disk of corrugated pasteboard the diameter of the disk is slipped over the central handle. This is a good insulator.

In Figure 6, the two curves represent sections of a sphere and of a paraboloid. It is evident that the parabolic curve is flatter at the margins, C, C, of the glass than at the central portion, D-D. Therefore light reflected from the pinhole will bring the rays from C and C to a point at B, on the axis of the mirror, further away than the point where the deeper part of the curve, D-D will focus them.

The distance between A and B is given from the equation, AB equals

the square of the radius of the mirror, divided by its radius of curvature. Substituting for our six-inch mirror of four-foot focal length, we have, AB equals $(3)^2$ divided by 96, or 9/96, which is about one-tenth of an inch.

We now diaphragm out all of the mirror except a half-inch around the margin, and mark on the table the position of the knife-edge when the light darkens equally over the exposed portions. All of the mirror is then covered except a central portion two inches in diameter, and the knife-edge test is again applied similarly. This time, if the surface is correctly parabolized, we shall have to move the knife-edge toward the mirror one-tenth of an inch, as above determined. In both of the above tests, what we are really doing is to select limited parts of the paraboloid and regard each part

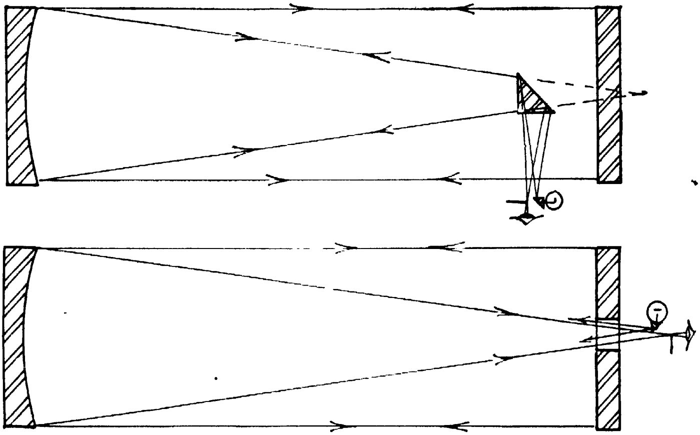


FIGURE 17. TWO METHODS OF TESTING AT THE FOCUS.

as locally spherical; and then determine the degree of parabolization by ascertaining the difference in focal length of the respective spheres.

Silvering is now in order. It was some time before I produced a good, tough, silver coating, but if I had had access to the information in Part VI there would have been no trouble.

Finally, if a lacquer diluted six times with amyl acetate, is poured over the mirror and allowed to dry with the glass on its edge, the lustre of the silver will be prolonged for years, without in any way impairing its optical properties.

I have intentionally selected the method of testing at the center of curvature as being the favorite among amateurs, notwithstanding the fact that it is not as rigorous as testing at the focus with an optical flat. Testing at the center of curvature is capable of yielding an acceptable glass in a reasonable time before the worker's patience has become quite exhausted. It

is far better in the interest of the amateur astronomer that he go far enough in the work to see and appreciate what a fair mirror will show him in the heavens, before he bogs down in the slough of despond and throws up the job as impossible.

A few years ago I tried out the method just mentioned with fifteen mechanics (taken at random from the industrial shops of Springfield, Vermont) and they all produced acceptable mirrors, and nearly all finished their mountings.

A reference to the method of testing at the focus will be interesting to one who has figured his mirror at the center of curvature. The set-up is shown in Figure 17, at the top. The optical parts are arranged just as they will be in the finished telescope, but with the addition of a flat, silvered mirror, placed as if it were just outside the telescope tube.

Light from the pinhole strikes the speculum via the prism, and if the mirror is correctly parabolized it goes out of the tube as parallel rays. It then returns by reflection from the flat, following back over its outward course and producing an image of the pinhole at the knife-edge. Thus, parallel rays are obtained, just as if they came from a distant star, and since they are parallel we may test at the focus instead of at double the focal length, as we formerly did.

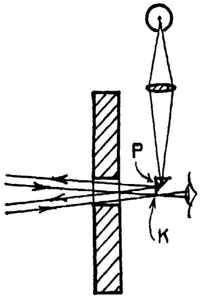


FIGURE 18.
A MODIFICATION OF THE SECOND METHOD OF FIGURE 17.

In other words, we have manufactured parallel light in the laboratory. This is the most rigorous method of testing, but it requires a flat the size of the speculum, and the flat is the most difficult of all surfaces to make.

In testing at the focus the pinhole and knife-edge must be brought close together in order to avoid the necessity of providing a large diagonal. This is accomplished by placing a small (¼″) prism over the pinhole, as shown in the upper figure. I parabolized about 100 6-inch mirrors by this method, modified as shown in the lower drawing. Here the flat had a central hole and the pinhole and knife-edge were located just back of it.

If these two arrangements are closely studied it will be seen that two reflections are avoided by the second. In the first, the light is reflected from the pinhole to the large diagonal, thence to the concave, thence to the flat, and returns over the same course in reverse order, to the knife-edge. In the second, however, the light goes from the pinhole to the concave, thence to the flat, and return via the concave, back to the knife-edge.

Thus in the first method there are five reflections, against three in the

second. Not only is this a great saving in light, but the ease with which the second arrangement may be put in adjustment and the image found shows at once the advantage of the second method.

An additional refinement is the introduction of a condensing lens between the light-source (I used a cylindrical acetylene flame) and the pinhole, and this is shown in Figure 18. This allows the lamp, with its unavoidable heat, to be removed from the vicinity of the flat.

I covered the front of the small prism P, with tinfoil in which the pinhole was perforated. Incidentally, the tinfoil was made to overlap the edge of the prism slightly at K, and thus it became the knife-edge itself. In this way I was enabled to keep both pinhole and knife-edge within only one-eighth of an inch of each other, permitting the use of a flat which happened to have a central hole less than an inch in diameter.

The amateur's attention should be called to the fact that the set-ups shown in Figure 17 are primarily intended for producing parallel light *artificially.* The returning light rays from the large flats are precisely like the light coming from a star, but with the great advantage that the rays are not affected by disturbances of the earth's atmosphere.

For testing at the focus, an ordinary engine lathe can be made into an excellent testing bench by removing the head and tail stocks, mounting the concave mirror on a suitable support at the head stock end of the lathe bed and fastening the flat and the lamp to the cross slide. Anyone who is familiar with the engine lathe will realize at once that the pinhole and knife-edge can thus be maintained in perfect control, both toward or from the concave, and at right angles to the axis of the mirror.

Nothing has been said here about scratches, effects of changed temperature on the glass, where best to work, testing with an eyepiece, the dreaded turned-down edge, sticking of the glass, the various strokes and altered laps, and so on. Ellison covers them all.

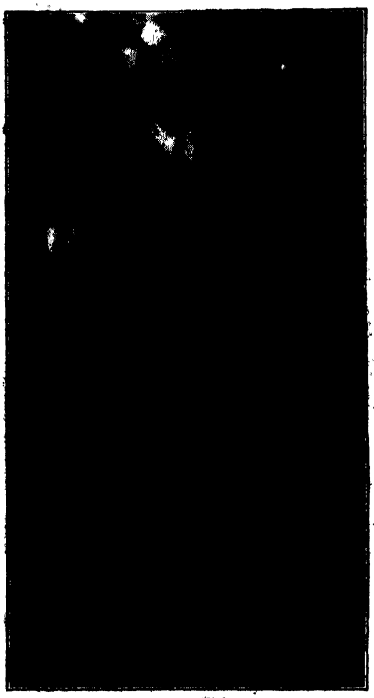
Sir Howard Grubb, the well-known English maker of telescopes, is credited with the remark that "when the mirror has been brought to a complete polish, the work is about one-quarter done." And while it is true that the long interval of figuring with its interminable testing, tries the soul of the amateur, let him take pride in the fact that he is dealing with—and controlling—minute errors a thousand times smaller than those dealt with by a mechanic or machinist; and in the satisfaction of knowing that with this mirror made with his two hands he will be able to see the polar caps of Mars, Jupiter's bands, Saturn's rings, nebulæ, clusters and double stars—an instrument that would have excited the envy even of Galileo and Newton.

My experience has been this, that anyone who can use his hands, is possessed of moderate patience and sufficient reasoning ability to interpret the knife-edge shadows, can make a good mirror. Without these attributes he had better forego the venture.

Mirror making has many points to commend it. The tools are easy to make. The cost of materials is (compared to results) low. The work may be carried on at odd moments, day or night and in any available room of the home. In short, it contains the elements of a real indoor sport.

STELLAFANE

Stellafane or "Stellar Fane" (shrine to the stars) as it was formerly called, is the little club-house-observatory of the "Telescope Makers of Springfield," perched on the summit of a fir-clad mountain three miles from that community in southeastern Vermont. The illustration gives only a meager impression of the equipment available. At the right, just out of the photograph, is the tower of a spectrohelioscope to be constructed similar to the one described in Part IX. At the rear (south) is a polar Cassegrainian telescope of the type shown in Figure 42 at VII; also the Sun telescope shown in Figure 52. Inside there is a star transit, a well equipped optical shop, an equally well equipped kitchen, sleeping quarters and a collection of telescopes which may be taken outside for use. Inscribed on the facia of the roof, in front, is the verse, "The Heavens Declare the Glory of God."



Photograph by Dr. Clyde Fisher

Russell W. Porter.

CHAPTER II.

Making the Mounting

Seated well up in the bleachers (Latitude 43 degrees N) we Vermont astronomers can command a fine view of the greatest of all spectacles—the solar system. In it, the race is always on. The entrants gain and lose on each other as they pass us by. Until Copernicus somewhat rudely shoved us over to one side we thought we saw the show at first from a central coign of vantage. However, the change was not all a loss, for it placed us on a movable platform where we became a real participant.

I always like to think of this old earth of ours as a gigantic piece of exquisite mechanism with which by the aid of a mirror of my own making, I am privileged to play at will. I pick it to pieces, watch it turn over and check up on its geometrical makeup. I then like to sense my exact place on this ball (for me this place is not quite halfway between the equator and pole), and,

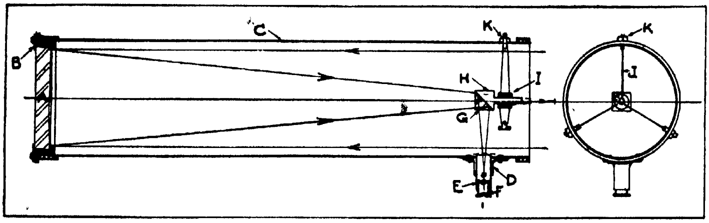


FIGURE 19

A TYPICAL NEWTONIAN MOUNTING—THE TUBE

It was Sir Isaac Newton who devised the method of using a small diagonal mirror to bring the rays to a conveniently located eyepiece. In place of such a mirror, an unsilvered diagonal prism costing only a few dollars, may be used to advantage.

from this vantage point as it swings around the sun, to watch our neighbor planets weaving their intricate paths through the stars. But before I may appreciate the beauties of this mechanism, my mirror, along with its prism and eyepiece, must be properly mounted.

The essentials of an efficient reflecting telescope mounting are: that the optical train, viz., mirror, prism and eyepiece, be held rigidly in relation to each other; that provision be made for conveniently adjusting these parts; and that the whole be supported on bearings, that will allow any celestial object to be easily followed as it moves across the sky.

The first of these conditions is readily met by the use of a tube of sheet metal to which the different optical parts are attached. Since the hollow cylinder is one of the stiffest forms for its weight and can be obtained of any tinsmith in galvanized iron at moderate cost, the advantage of its use is obvious. The mirror A (Figure 19) rests in the cell B, fastened to one end of

the tube C. The eyepiece F, fits into another tube E, called the adapter, which slides easily in a flanged piece D fastened to the side of the telescope tube. The prism G (hypothenuse side) is held against a corresponding face on member H. A stud on the rear of H, fits in the sleeve I, which is held to the telescope tube by the three knife edges J. The knife edges have threaded ends, they rest in slotted holes in the tube and are provided with set nuts. With this arrangement the prism may be adjusted to bring it into proper relation to the mirror and eyepiece.

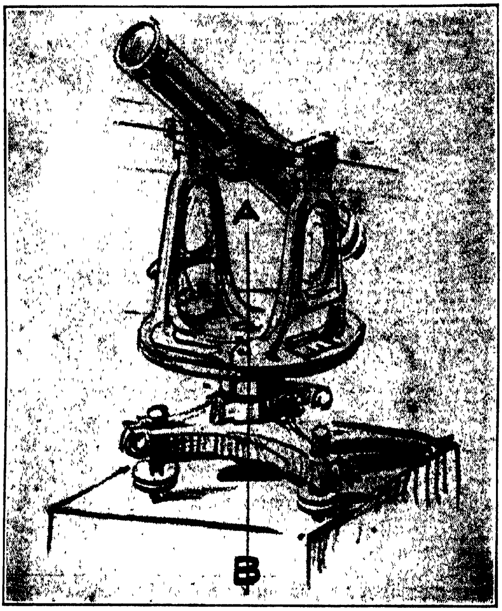


FIGURE 20

THE SURVEYOR'S TRANSIT

With its vertical axis, A-B, plumbed up, this type of mounting requires constant slow motion in two planes, in a series of steps, or zig-zags, in order that it may follow the stars.

This solution of our first and second essential conditions is the one now in almost universal use. The optical parts are easily removed without disturbing their adjustments when taken indoors for safe keeping. An additional refinement is a focusing rack and pinion. Sometimes a diagonal, flat piece of glass (silvered on its front surface) is substituted for the prism, but this is not

advised on account of there being added thus an unnecessary silvered surface which has to be protected. The prism, on the other hand, is not silvered and is totally reflecting, owing to the acute angle at which the light meets its hypothenuse side.

The tube must now be so supported as to follow the stars. Of the several ways this may be accomplished, one condition underlies them all—there must

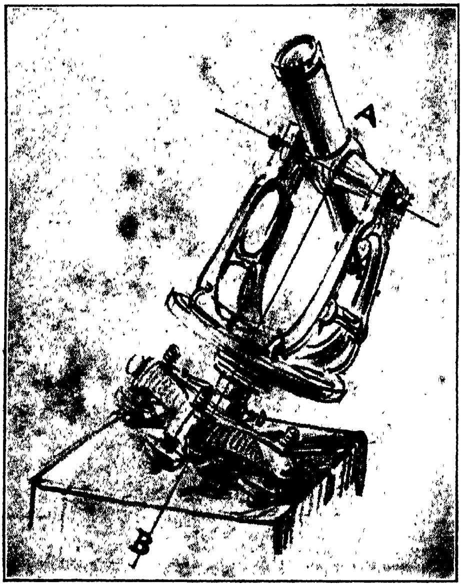


FIGURE 21

THE EQUATORIAL MOUNTING

The transit of Fig. 20 has now been tilted until its axis, A-B, is parallel to the earth's axis. It will now require slow motion in only one direction instead of two. Fig. 22 explains the theory of this change.

be provided two bearings at right angles to each other and one of them must be capable of being adjusted parallel to the axis of our earth. A familiar instrument having these two bearings at right angles to each other is the surveyor's transit or theodolite. One of the axes, A-B (Figure 20), is always plumb. Imagine the instrument tipped over until this axis is parallel to that

of the earth (Figure 21), and we have what astromoners call an equatorial mounting. The axis about which the telescope swings is called the declination axis.

To visualize this condition of parallelism between the polar axis of the mounting and the axis about which the earth rotates, I have drawn Figure 22. In this schematic diagram a mounting is shown placed on the earth's surface in about the middle latitude of the northern hemisphere. Its polar axis

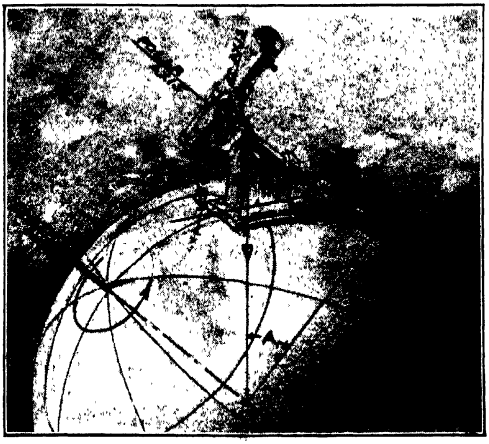


FIGURE 22

THE "WHY" OF THE EQUATORIAL MOUNTING

First, in any equatorial telescope, the angle A, between the polar axis and the northern horizon, must equal the observer's latitude. Once adjusted thus, it need never be touched—unless the telescope is moved to another latitude. The polar axis is now parallel to the earth's axis, and although these are several thousand miles apart, this makes no appreciable difference in observing objects millions of times as far away. Having now eliminated this factor, any star may be followed by slowly revolving the declination axis and telescope tube as a whole around the polar axis. Whether we now choose to point the tube high or low in the skies makes no difference—wherever it is, its polar axis is always performing the necessary slow motion to offset the earth's daily rotation.

and the earth's axis are seen to be parallel to each other. At right angles to the polar axis is the declination axis about which the tube swings, allowing it to be pointed at any angle with the observer's horizon.

The earth, turning in the direction of the arrow, gives the stars an apparent motion in the heavens in the opposite direction, and a slow motion of the polar axis spindle of just the right amount will keep any star (regard-

less of its elevation above the horizon) constantly in view in the eyepiece of the instrument. When the telescope is pointed toward the pole of the heavens, stars move across the field of view slowly. Polaris, for example, seems hardly to move during an entire evening.

But as the tube is now swung down toward the celestial equator, the apparent motion of the stars is accelerated. Thus, the motion of the moon in a high powered eyepiece is so rapid as to give an almost overwhelming realization that the earth is turning over in space. Were the mounting to

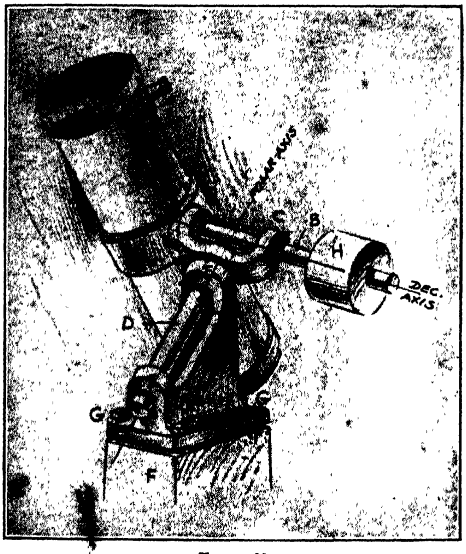


FIGURE 28

THE GERMAN TYPE OF MOUNTING

This is the commonest of the equatorial types. It has many advantages and comparatively few drawbacks.

be erected at the earth's poles, the polar axis would, of course, be *vertical* to the observer's horizon; if placed anywhere on the earth's equator it would be *horizontal,* or parallel to one's horizon. However, the great bulk of us humans live somewhere about midway between these two extremes, and in any case the polar axis of one's mounting makes an angle A with his northern horizon equal to his latitude, for the two angles A, A, are always the same, as is evident from the two triangles shown.

Of the several types of mountings the most common type is known as the German mounting. (Figure 23.) The tube fits into a ring A, to which is attached a spindle B. The bearings C, C, for this spindle are at one end of spindle D, and D's bearings, E, E, are part of the casting fastened to the pier F. When D is adjusted by the screws G, parallel to the earth's axis, any object in the telescope eyepiece will be held in the center of the

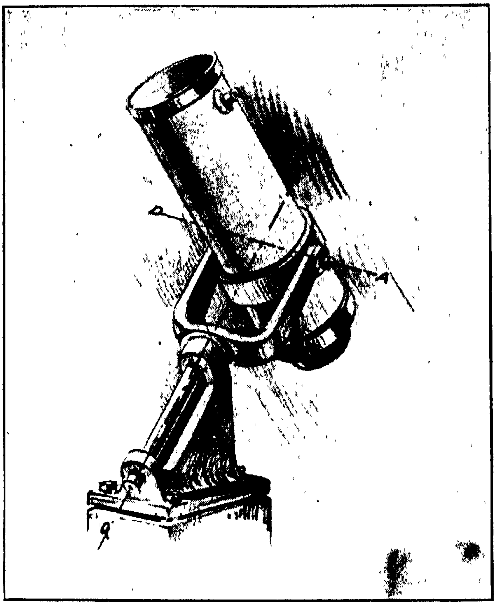


FIGURE 24

THE ENGLISH, OR FORK TYPE

It dispenses with counterweights, but it is not as rigid as some others, due to its long overhang over the bearing. P-A is the polar axis, D-A is the declination axis.

field by revolving the instrument about D just fast enough to counteract the diurnal rotation of the earth.

This type of instrument is completely counterbalanced, and the tube is gripped at such a point that it will remain pointing in any position without clamping. Since it overhangs one side of the polar axis, sufficient weight H, is added to the opposite end of the declination spindle in order to bring the center of weight into the polar axis near its upper bearing. The total

weight is, therefore, inside the base and is equipoised. Usually, for convenience in following a star, a worm and worm wheel are provided on the polar spindle.

In the English or fork type, Figure 24, the tube is swung in a yoke attached to the upper end of the polar spindle but considerably overhanging

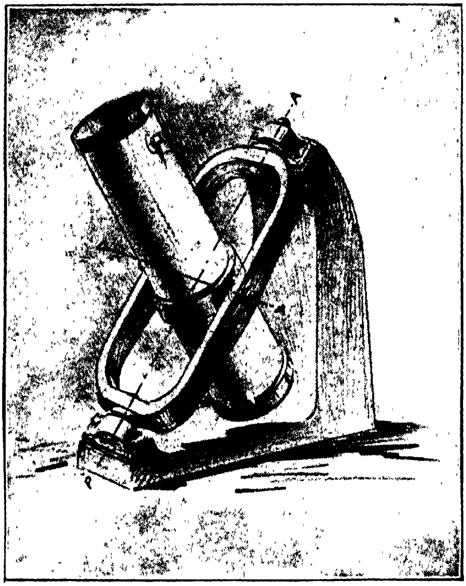


FIGURE 25

THE DOUBLE YOKE TYPE

Compare this with Fig. 24. Being included within two bearings, the tube is very stable. There are no counterweights. Part of the northern heavens is, however, inaccessible. The famous Hooker telescope at the Mt. Wilson Observatory, near Pasadena, California, with a 100-inch mirror, has this type of mounting.

the pier. This type has the advantage of requiring no additional counterweights.

This excessive overhang of the tube in the fork form just described is overcome in a third type where the tube is brought within the two bearings of the polar axis, whose spindle is enlarged into a double yoke, within which the telescope swings in declination, Figure 25.

However, all forms of mountings are compromises, and in the last-named type, the gain in rigidity is obtained at the cost of cutting off from view a part of the northern heaven. It is interesting here to note that this was the form of mounting which was adopted to carry our greatest of all mirrors—the 100-inch reflecting telescope at Mount Wilson, California.

Still another form is obtained by expanding the upper bearing of the

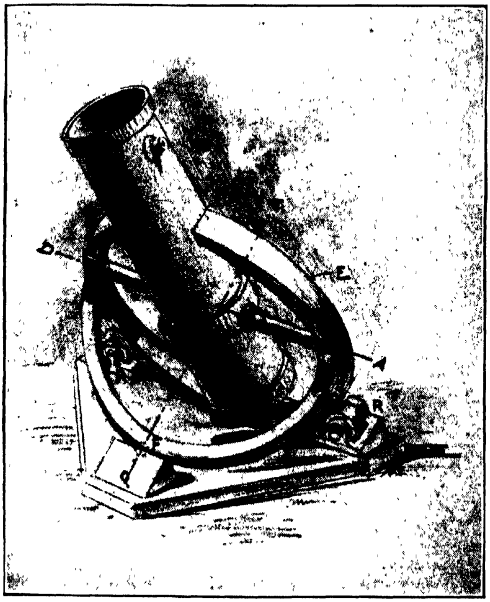


FIGURE 26

THE EQUATORIAL RING TYPE

The ring revolves on rollers, R, R. The polar axis is P-A, and the ring rolls in a plane parallel to the earth's equator. This type is especially steady.

polar axis to a large equatorial ring E, Figure 26, within which the telescope swings on its declination axis, the lower end of the polar axis having a thrust bearing at F. The large ring turns on the two rolls R, R. This type of mounting is very stable, the center of weight of the moving parts being well within the supporting rolls and thrust bearing. Part of the equatorial ring E, is cut away in order to allow the tube to reach all parts of the heavens.

In all of these mountings considerable machining of parts is required, as well as special castings running into a lot of money, thus putting them beyond the means and capabilities of most amateurs. The *Springfield Telescope Makers* selected the first of the types just described, the German form. But they had access to the resources of the machine shops here and were all skilled mechanics. I shall, therefore, at risk of possible criticism, describe a wooden equatorial mounting containing the essential features, but which may be very easily put together from materials available anywhere. When the mirror maker has given his glass a good tryout with this mounting he will either be satisfied with it, or he will become so enthused with its performance, that he will attempt something better in metal.

To hold the optical parts a clear, straight-grained plank of pine or spruce A, Figure 27, 1½ inches thick, 6 inches wide at the mirror end and tapering to 2 inches at the other, is used. The mirror rests in a one-inch board 6½ inches square screwed to A as shown and recessed for the mirror to a depth of one-half inch.

In order to forestall the possibility of the mirror falling out of its cell, wooden buttons or brass clips may be distributed around the edge of the recessed board. At the back of this shelf there are three adjusting screws on which the mirror rests. At the other end of A a hole is bored to take the tube C. C is a piece of brass tubing about 6 inches long, with an inside diameter equal to the diameter of the eyepiece to be used. One end of C is cut down, leaving two ears at I, with enough spring in them to grip and hold the one-inch, totally-reflecting prism. Some of the tube between the plank and prism is cut away in order to offer no more obstruction to incident light on the mirror than is necessary to support the prism. The other end of the tube is slotted in order to allow the eyepiece to slide for focusing. So much for the member holding the optical parts. When assembled, find the point on A where it balances and bore a ½-inch hole.

D is a block of wood 6 inches square, and 2¼ inches thick. Part of one side, within a four-inch circle, is recessed ⅛-inch. Unfortunately this circle was not indicated on Figure 27. Two holes, respectively ½-inch and 1-inch in diameter, are now bored through the block as shown. When finished it is attached to A, using a ½-inch bolt 4 inches long provided with washers and a butterfly nut.

The polar axis is a piece of one-inch shafting about 2 feet long. Have the blacksmith bend over 6 inches of it until it makes an angle with the rest of the shaft about equal to the complement of the observer's latitude.

The remainder of the mount consists of a 2-inch steam pipe, 2 feet long, cast vertically into a concrete pier. When the bent end is adjusted parallel to the earth's axis by lining it up on Polaris some evening, concrete is poured into the steam pipe, and allowed to set, the block D is dropped down over the shafting in the hole provided for it, and the mount is finished.

The butterfly nut will give the desired pressure between A and D so that the telescope will turn, and will remain fixed at any required declination. If D is slotted as shown, the wood screw M, will take up any looseness of the bearing of the polar axis. The mirror is adjusted in its cell until

its optical axis passes through the center of the prism (see J, Figure 27). The adjustment is tested by placing the eye well behind the prism and noting whether the reflection of the prism is in the center of the mirror. Should it be found, say, at K, unscrewing the screw L, will make the reflection move toward the center.

The prism is adjusted by taking out the lenses of the eyepiece and looking

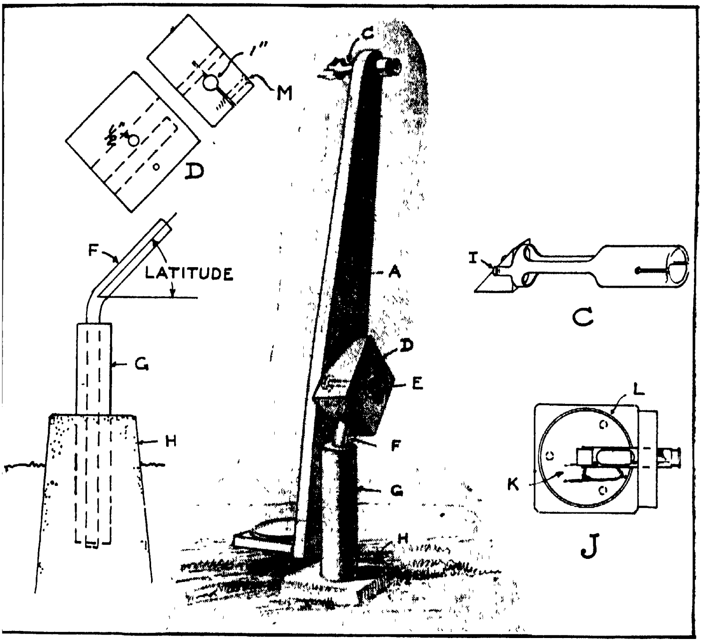


FIGURE 27

A WOODEN, EQUATORIAL MOUNTING THAT ANYONE CAN MAKE

Although it is inexpensive and simple, the amateur who lacks access to machine tools will find this a very serviceable mounting. If care is used in bending the shafting F properly, and setting it approximately parallel to the earth's axis, the telescope will need to be moved in only one plane in order to follow a star for considerable periods of time.

into the adapter. The reflection of the mirror will be seen in the prism. The reflection of the prism should be central and must be made so by filing the seat of the prism. A slight movement of the prism between its ears will

cause the reflection of the mirror to move and this will indicate where the seat should be altered.

The focal length of the mirror has previously been found during the knife-edge tests. It is one-half its radius of curvature. The distance from the surface of the mirror to the center of the adapter tube will therefore be this focal length less the distance (about 5 inches) from the center of the prism to the focus of the eyepiece. From mirror to adapter would be $48 - 5 = 43$ inches for a glass of four feet focal length. The focal plane of

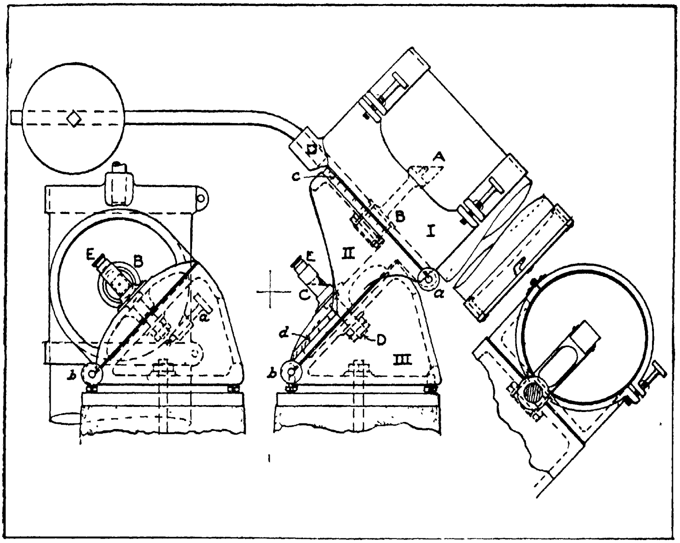


FIGURE 28

FRONT AND SIDE ELEVATIONS OF THE SPRINGFIELD MOUNTING

*This is the mounting shown in Figs. 30 and 31. (This type was originated by Porter.—*ED.)

a negative eyepiece is somewhere between its component lenses; of a positive eyepiece it is just in front of the field lens.

It will be observed that for zenith stars (objects overhead) the eyepiece will be found about at the height of the eye when standing. For objects at a lower altitude a chair or stool will be found convenient. The wooden part of the mount should be well painted and the polar axis should be kept slushed with hard grease. The wooden member can be lifted off the polar axis and taken indoors as a whole, for it is quite light. A cap of

some sort (a piece of window glass will do) should always cover the mirror when not in use, in order to preserve the lustre of the silvered surface.

One of the most convenient of equatorial mountings (Figures 28, 30, 31), and the one producing the most satisfactory results here at Springfield, Vermont, has the advantage of a fixed eyepiece. It is true a second prism is required, but this permits the observer to sit in one position for all celestial objects, looking comfortably down the polar axis. The two controls in right ascension and declination are within easy reach (Figure 30), the setting circles are large and need no verniers. The tube is counter-

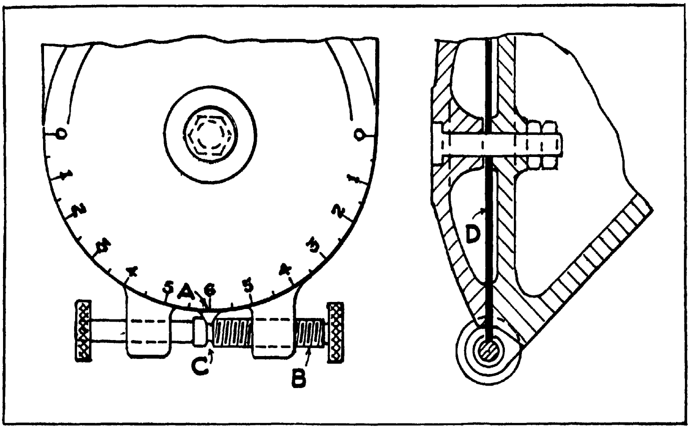


FIGURE 29
DETAIL OF THE SLOW MOTION, SPRINGFIELD MOUNTING
Front and side elevations. This is a part of Figure 28

poised and can reach all parts of the heavens. Loss of light, due to the addition of an extra reflection, is negligible.

Light from the mirror, after reflection from the usual prism A, in the tube (Figure 28) passes through the hollow declination stud B, to another prism C, directly over the polar axis stud D, and below the eyepiece. In addition to its fixed eyepiece, a distinctive feature of this mounting is the manner in which the two axes are maintained. Instead of two spindles held in bearings at their extremities the bearing surfaces consist of large areas held together with small central studs, that of the declination axis being hollow. This arrangement permits very rigid forms of the three castings I, II, and III. The setting circles c and d are cut on member II in convenient positions for reading.

Control in motion is as follows: The two tangent screws a and b,

(Figure 28) bear against spurs on the edges of two thin sheet steel disks inserted between castings I, II and III. Figure 29 shows the detail of the slow motion about the polar axis. The spur A, on the periphery of disk D, bears in the circular groove C, of screw B. Sufficient friction is maintained between the bearing surfaces of the disks so that not only will the tangent screws produce slow motion on either axis, but will also allow the telescope to be swung quickly through large arcs of the heaven in both declination and right ascension. This arrangement makes a very good substitute for the expensive worm wheel drives.

Of the many designs of mountings which enable the observer to sit in comfort in an enclosed and warmed room, lack of space here forbids. The most notable of these among amateurs is the Hartness Turret, in which

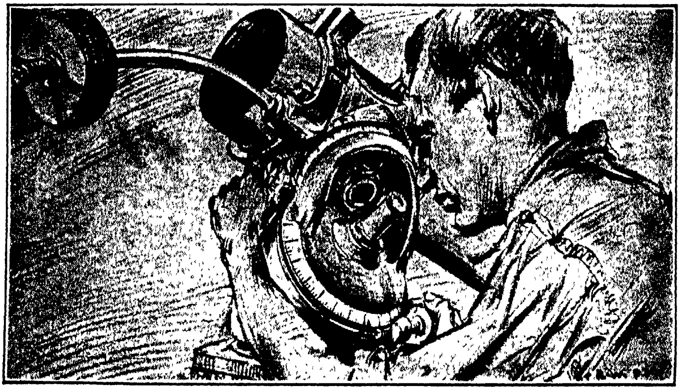


FIGURE 30

THE SPRINGFIELD MOUNTING, WITH DETAIL OF SETTING CIRCLES

Everything is within easy reach and vision. Note the slow motion screws for following the stars. This mounting may be made by a machinist, from blueprints.

the roof of the building, made of cast iron, and rotating on rolls, carries the optical parts and delivers the light from a 10-inch objective to an eyepiece inside the room. Bell, in his book, *The Telescope,* describes several of these instruments.

Of reflecting telescopes, apart from their mountings, mention has only been made here of the Newtonian reflecting type. There are, however, others, but they are not as practicable for the amateur as the Newtonian.

In the Gregorian, a small concave mirror just outside the focus, reflecting the light from the mirror to a secondary focus behind the mirror through a central hole in the glass, is substituted for the prism. The Cassegrainian is similar, but it interposes a convex mirror just inside the focus. Both of these

combinations greatly increase the virtual focal length of the mirror without increasing the length of the tube, but they are useless for day work on

FIGURE 81

THE SPRINGFIELD EQUATORIAL MOUNTING

The observer's position is fixed and comfortable. The light from stars in any part of the heavens reaches his eye via two prisms. Thus, instead of being forced to assume many uncomfortable observing positions, the astronomer is always looking down, as if he were using a microscope.

terrestrial objects, unless equipped with special shields, and they require the figuring of an additional optical surface.

With an equatorial mounting provided with setting circles, the astronomer can select any celestial object (above the horizon) by looking it up in the Nautical Almanac and setting the circles to the correct declination and hour angle. He also sets his watch running on star time. If he has made no blunder in his calculations, and if his instrument is in fair adjustment, the object will appear in the field of view of the eyepiece. It may be an obscure double star, or a nebula, or a cluster, or a comet, wholly invisible to the naked eye and impossible of finding in any other way.

Thus is seen the desirability of a mounting provided with circles if one wishes to delve into the great storehouse of hidden wonders above us.

On the other hand, the simple wooden mounting I have described will enable one to pick up all the apparent celestial bodies—the moon, the planets, sun spots, bright double and multiple stars, two nebulae which are visible to the naked eye and one or two star clusters.

Care must be taken in observing the sun, for the mirror makes a powerful burning glass. It works best for this purpose while unsilvered, but if it is already silvered, cover the glass with a cardboard in which an inch hole has been cut. The safest way is not to use the eye at the eyepiece but to project the sun's image on a card placed outside the eyepiece.

It is hoped that the amateurs will not copy these mountings slavishly, and partly for this reason, set dimensions are not given except in a few instances. When controlled by a clear comprehension of the principles of the mountings used and some mechanical judgment, the exercise of the amateur's individuality in planning his telescope is highly desirable. For example, Mr. Ions, formerly of Texas, has built a very ingenious equatorial mounting almost entirely from discarded parts of a Ford car.

The above suggestion regarding the exercise of some degree of individuality will, it is hoped, obviate the production of a large number of telescopes, as like as a lot of peas.

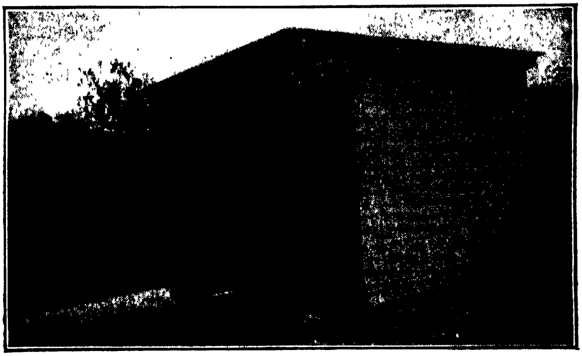
Eyepieces

Eyepieces or oculars for astronomical telescopes are usually the Hyghenian, set in 1¼ inch tubes. Their powers vary according to their equivalent focal length *(e. f. l.)*. For our telescope of 4-foot focal length an eyepiece of 1-inch *e. f. l.* would give 48 magnifications (the focal length of the mirror divided by the equivalent focal length of the eyepiece, gives the total magnification). A ½-inch eyepiece would give 96 magnifications, and a ¼-inch 192, respectively. This makes a good battery of eyepieces for range of powers. They cost from about six to ten dollars apiece. It is not advised to use a higher power than ¼-inch *e. f. l.* as the atmospheric disturbances and the quality of the mirror surface set a practical limit to the degree of magnification.

Were I to have but one eyepiece at first it would be the lower power, viz., 1-inch *e. f. l.* The Hyghenian eyepiece is not, however, achromatic, and the color is quite noticeable in a mirror telescope. I have used almost exclusively, the Hastings three-lens, positive oculars, as giving a beautiful, flat and colorless field.

Eyepieces from old microscopes are not to be despised and they work very well with a mirror. They are usually of low power and are useful for terrestrial observation.

A finder is a small telescope fastened to the eyepiece end of the telescope as an aid in pointing the tube to any desired and visible object, and it is undoubtedly a convenience in picking up a star quickly, although we usually get along here in Springfield by sighting along the tube itself. Of course, with one's mounting provided with setting circles in good adjustment, a finder is unnecessary.



A SIMPLE, PRACTICAL HOUSING

It is mounted on wheels or rollers running on a track at ground level. This is a 9-inch telescope made by Ritchey, for the Pasadena, California, High School. This photograph was furnished by the "Amateur Telescope Makers of Los Angeles."

CHAPTER III.

A Sun Telescope of 100-Foot Focal Length

This is not as ambitious as it sounds. The only optical parts needed are two 6-inch mirrors, one of them concave, the other flat.

The arrangement is shown in Figure 32, which requires little explanation. The fixed mirror is placed on the southern side of the house, opposite the room into which the sun's image is to be thrown, and distant from the window a few feet less than its focal length.

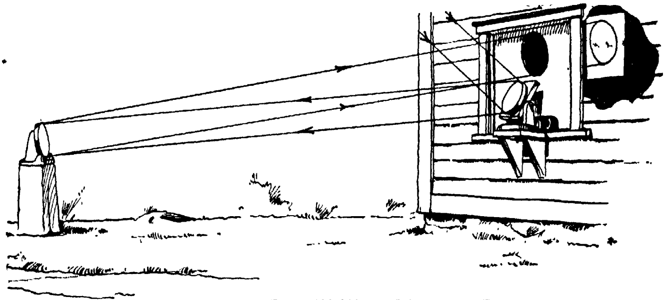


FIGURE 32. THE 100-FOOT SUN TELESCOPE.

The flat mirror is placed on a shelf on the windowsill and is manipulated from indoors in such a way as to catch the sun's rays and project them to the concave mirror in the yard. Using a 6-inch mirror, the image of the sun, as thrown on a screen inside the house, will actually be larger than the mirror itself. It will be bright and strong.

The screen may be a square of white cardboard on which the sun's disk will show up to good advantage, displaying the spots, etc.

Such a sun telescope, with a pair of 16-inch mirrors, was set up at *Stellar Fane,* near Springfield, Vermont, and was described in the November, 1925, *Scientific American.* We removed the entire window sash and substituted a shutter of beaver board having a hole just large enough to let in the sun's image. Our 16-inch concave mirror (of 75-foot focal length) had, however, to be diaphragmed down to only four inches effective diameter.

In order to show the detail more closely, the scale of Figure 32 was purposely distorted. The two axes of the flat and the method of controlling them in order to offset the sun's motion are shown in the diagram. The mirror rests on a wooden block which can be tilted about a horizontal axis, and the whole is capable of being rotated around a vertical axis consisting of a stud which projects upwards from the shelf. The whole apparatus thus constitutes an alt-azimuth mounting, similar in principle to that shown in Figure 20.

With this sun telescope a whole roomful of people can study the sun spots, which show with considerable detail.

In testing a flat surface, which may be done at the center of curvature of a spherical mirror (see Figure 33), it is manifest that if a sphere *appears* flat with the knife-edge at its center of curvature, the introduction of a perfect plane surface at A will not alter the appearance of the sphere, which is now seen as if it were placed at B. Therefore, any departure from a flat surface will produce raised or depressed areas superposed over the apparent flatness of the sphere. These must be removed by figuring, just as though you were working on the spherical surface alone, as explained in Chapter I.

Thus, to determine whether the flat is concave or convex, locate the position of the knife-edge as it comes in from the side, where the shadow darkens uniformly (as in testing a spherical mirror). Then test with the knife-edge coming down from above. If it shortens the radius of curvature the flat is concave. If it lengthens the radius it is convex. This effect is due to foreshortening, the flat being at an angle of 45° to the axis.

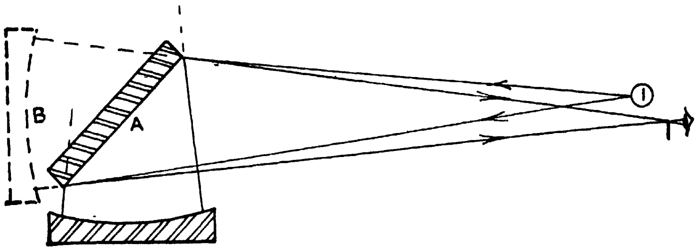


FIGURE 33. FIGURING A "FLAT" WITH A SPHEROIDAL MIRROR.

If the second arrangement of Figure 17 is used for testing, the hole in the flat should be made after the figuring. With ordinary commercial plate glass, this will result in a slightly turned-up edge around the edge of the hole, like the rim around a crater (due to strains in the glass). However, this distortion extends to so short a distance from the hole that it need not trouble the amateur in parabolizing.

A better way to produce an annular flat is to cut out the central portion first and cement the core of glass back into its hole again with plaster of paris. The glass is then fine ground, polished and figured to a flat as one surface, and the core is afterward knocked out.

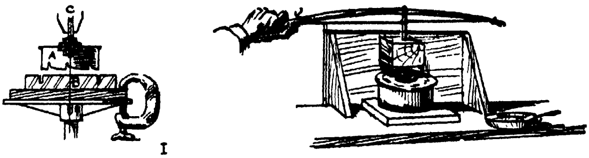
The concave mirror has too great a focal length to be tested with the knife-edge, for the shadows would be altogether more subtle, even, than those of the long focus paraboloid whose shadowgraph is shown in Chapter I. The mirror will therefore be fine ground for only a few moments (using, for convenience, the back of the flat as a tool) until the thinnest of tissue paper can be inserted between its surface and a straight-edge. It is then polished, taking great care to maintain good contact. Let us hope it is close to a spherical surface.

CHAPTER IV.

Wrinkles

Here is a way to cut out a circular disk of glass from a slab. Assuming that we have access to a drill press, we proceed as follows: A cutter is made by fastening a tin can to a bolt, as shown in I, Figure 34. The can *A* is cut down, leaving walls about twice as long as the thickness of the glass to be cut. A hole large enough to take the bolt is punched through the back of the can, washers and nuts are added loosely. The bolt end is then inserted in the chuck *C* of the drill press. Shift the can on the washers until it runs smoothly, then screw the nuts home.

The glass slab *B* is pitched to the board and clamped to the table. Carborundum (about No. 200) and water are fed under the cutter, and in about half an hour the slab will be cut through. The cutting edge of the can, though not perfectly circular, will, however, cut out a perfect cylinder from the glass. If



I II

FIGURE 34

the cutting edge is notched as shown, it will cut faster. The drawing shows the slab nearly cut through.

The old fashioned bow drill (II) will cut small disks if a drill press is not available. The set-up required needs no explanation. Of course the bolt must be longer than the one used with the press.

"Sleeks" is a term applied by glass workers when for some unknown reason a number of very fine scratches appear on a glass surface during the polishing. They are so fine as to be indistinguishable unless the glass is held up to the light and its surface viewed by reflection. It is said by English opticians that if the pitch lap is thoroughly dried, a few moments of vigorous dry polishing will remove them. My experience has been that they appear only during the last stage of figuring.

It is always desirable that the walls of the telescope tube reflect no light into the eyepiece. In refractors this is prevented by placing diaphragms along the inner wall of the tube at certain intervals. Turpentine added to ordinary black paint gives a good dull surface; coach black, used for blackening the interiors of cameras and other optical instruments, is the best of all. Brass tubing may be given a permanent dull black surface by thoroughly cleaning the tube and immersing it in a saturated solution of nitrate of copper. Pieces of copper are dissolved in nitric acid until it will take up no more. The

tubing is hung on a bent wire, immersed and held in an alcohol or gas flame until the darkening brass assumes an even shade.

A diagonal such as is used on the Springfield Mounting may be assembled from the parts shown in III, Figure 35. The two pieces *a* and *b* are cut out with a hack saw from a sheet of brass one-sixteenth inch thick. Piece *b* is bent along the line *AA* to a right angle and the two holes are then drilled out and filed smooth. The short section of tubing *B* is to fit the eyepiece, and the longer tube *E* the adapter, and the two holes are made correspondingly, but a little smaller in diameter. The back plate *a* is then screwed to *b*, using the smallest brass machine screws obtainable; the ears *DD* are bent up to prevent the prism from falling out. The prism should fit fairly loosely. Shim up

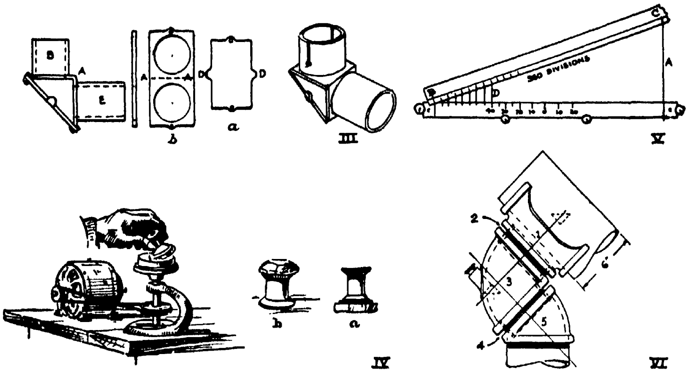


FIGURE 35

with paper on the hypothenuse side until there is no shake. After the prism has been fitted, remove it, screw on the plate again and solder on the two tubes.

If a revolving spindle can be found or rigged up, a small double or plano-convex lens is not a difficult thing to make, especially in this mechanical age with small electric motors in such universal use. The end of the motor's armature shaft itself will do on a pinch, but it is easier to belt off to a vertical spindle. Even the bow drill can be resorted to if necessary. Of course the calculation of the curves of lenses and the kinds of glass to be used in making a telescope objective are beyond the purpose of this chapter, but a simple magnifying glass of, say, an inch in diameter can easily be made.

With a tin can about an inch in diameter, cut a disk from a piece of broken wind shield or looking glass, as previously described. Pitch the disk to a small piece of wood, such as a spool, for a handle, as in IV, *a*. Grind down the edge

on a piece of glass or iron until it is roughly convex, like *b* in the figure. Cut out another disk of the same size and pitch it to the spindle. Turn on the motor just before the pitch becomes hard, and with the thumb and forefinger steady the disk until it runs concentric with the spindle.

Start grinding the roughed out disk on the glass tool, using the same grades of carborundum as in mirror making. Give the spool a rocking motion, very much like that of a spinning top before it is going to fall. Very soon the lens will take on a smooth, curved surface, and a cup-shaped depression will begin to form at the center of the tool. By the time this cavity has reached the edge of the tool the curve of the lens will have flattened considerably. Bring the glass to a fine-ground surface (it will surprise you to see how quickly it is done, in contrast to hand work), clean the tool, spread on a sheet of honeycomb foundation and polish. The polish should be complete in about 15 minutes. Whittle down a spool until it fits the adapter of your silvered glass telescope. Stick the lens to one end of the spool with a little pitch and try it as an eyepiece on the Moon. Probably you will be happily disappointed.

On equatorial mountings having setting circles there are two graduated circles—one in degrees for declination settings, the other in hours and fractions thereof—for setting off the hour angles. If desired these graduations may be cut on the castings in a machine shop, but this is an expensive operation and the cost can be circumvented by going about it in this way: Prepare two strips of thin sheet brass half an inch wide and long enough to go around the castings and overlap a little. Wrap them tightly and make a scratch where they overlap. Then fasten one of the strips to a drawing board with thumb tacks, as in V, Figure 35, and draw the perpendicular *A*. Place a scale on the board at such an angle that there will be 360 divisions between *B* and *C*. These divisions are now to be transferred to the strip by dropping the perpendiculars *D* and scratching them into the brass with a sharp tool like a knife blade. Every tenth division is made longer than the others and numbered, starting with zero at the middle and increasing to 90 either way, and then back to zero at the ends: 0, 90, 0, 90, 0. This is the declination circle.

The strip for the hour circle is similarly treated, except that here there are but 144 divisions divided up into 24 hour divisions, each hour subdivided six times, giving a least count of 10 minutes of time.

The precision obtainable by making the circles by hand in this manner is enough for setting purposes, for all that is needed is an accuracy sufficient to bring any star desired well into the view of a low power eyepiece.

Pipe connections have been used in building equatorial mountings. I would offer as a suggestion the availability of the large 6-inch connections shown in VI, Figure 35, as a substitute for the rather expensive castings of the Springfield mountings. They would comprise the "T" (1), close nipple (2), 90-degree elbow (3), close nipple (4) and 45-degree elbow (5). These parts ought to move very smoothly on the threaded nipples, since the threads themselves are tapered and can be screwed together until they bear freely on each other with little shake.

One way of making a stand suitable for the coelostat of the sun telescope described in Chapter III, is indicated below. One stand, made of wood, is shown at I, Figure 86, and another, of metal, at II. The board holding the flat mirror is hinged at *A* to another board *B*, with a stud passing through it into the bracket shelf below. With hard grease between board *B* and the

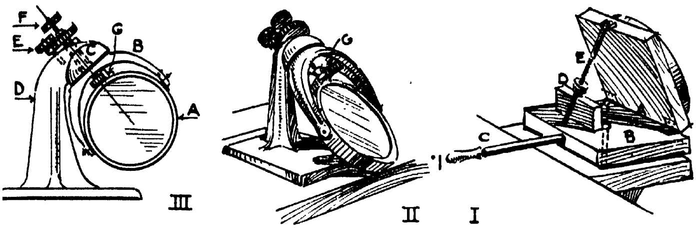


FIGURE 86

shelf below, the handle *C* will turn the mirror in azimuth and the nut *D* on the threaded rod *E* will raise and lower the mirror.

This last is not, however, so good as the equatorial mounting shown at II in perspective, and in section in III. The mirror cell *A* is swung in the inverted fork *B*. The hollow spindle *C* of the fork passes through the standard *D*. Motion in right ascension is transmitted through pinion *E*, and in declination through pinion *F* which engages a short section of a curved rack *G* fastened to the side of the cell.

The best time for viewing the Sun's image is early in the morning before the air has become badly disturbed by convection currents, or on sudden clearing after a cloudy day. The Sun's image will be about 10 inches in diameter and just bright enough to be viewed comfortably with the naked eye. It is surprising how rapidly the image moves across the screen, and it

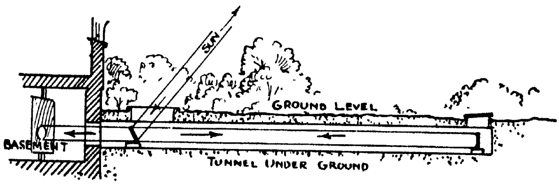


FIGURE 87

is interesting in this connection to note that we have here a brilliant image twice the diameter of the mirror that produced it. This shows forcibly that the diameter of the glass has nothing whatever to do with the magnification—the size of the image is a function of the mirror's focal length, only.

It is probable that the steadiness of the image would be markedly improved if the Sun's rays between the two mirrors passed, say, through or under foliage or trees. The air in the shade of vegetation is much less disturbed than air over exposed earth or rocks. At "Stellafane," near Springfield, Vermont, the Sun Room is upstairs and we think much of the unsteadiness is due to the heat rising along the southern wall of the building. The best arrangement would probably be to get as much as possible of the apparatus underground, finally throwing the image into the cellar as shown in section in Figure 37.

The intriguing feature of this form of telescope is that such a powerful instrument may be obtained with so little labor and expense. Furthermore, it brings astronomy into the daylight hours, and it gives quite a thrill to be able after breakfast to turn on the mirrors and see how the Sun spots are behaving. Of course the Sun, prodigal with her light, is the only heavenly body furnishing enough light for such a telescope, which is useless on the Moon or stars.

A 6-inch Cassegrainian with flat and non-perforated primary, made by H. O. Bergstrom of North Platte, Neb.

CHAPTER V.

Adjustments

The following instructions for adjusting the optical parts of a silvered glass telescope apply to any one of the mountings already described—in fact, to any reflecting telescope of the Newtonian form. If the three optical parts are not in correct relation to each other, a star's image will have a flare or tail to it, and no matter how carefully one focuses his eyepiece, he will be unable to get fine detail on whatever he is studying.

Remove the lenses from the eyepiece and insert what is left of it in the adapter tube. If the eye is brought close up to the hole in the eye cap of the eyepiece, one sees (Figure 38, I) first, the walls of the adapter tube *B*, next (by reflection through the prism) the mirror *C* in its cell.

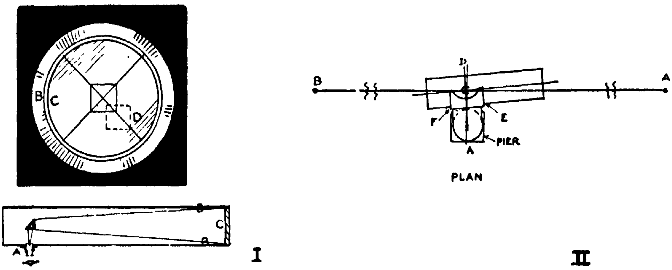


FIGURE 38

In the mirror will be seen a reflection of the prism itself, and if the mirror is in adjustment the prism will appear exactly at the center of the mirror where the threads temporarily stretched over the mirror cross. If the image of the prism shows at *D*, for example, then the side of the mirror near *D* must be moved away from the prism itself until the prism image is brought central. If the mirror itself is not seen centrally placed in the adapter the prism is out of adjustment and must be moved until *B* and *C* are concentric.

If a star's image is round and sharp, the adjustments are good, but if there is a flare, then the side of the mirror toward which the flare is pointing should be moved away from the prism.

These are the simple yet efficient means of adjusting the optical parts of the telescope. We now come to the adjustment of the mounting so that its polar axis will be parallel to that of the Earth. With the two wooden mountings previously described, it will be sufficient to line up their polar axes with Polaris at any time of the night. In the case of the double fork a sight line is provided along the edge of the yoke itself, and in the all wood mounts one can line up the bent shafting. I shall, however, use the Springfield Mounting on account of its having setting circles, for the principal object in adjusting

an equatorial mounting is to be able to find the many interesting celestial objects given in many books written especially for amateurs, and to do this, setting circles are indispensable.

Let us first make sure that the axis of the mirror is at right angles to the declination axis. It is taken for granted that the declination and polar axes are square with each other. With the declination axis horizontal (see plan, at II) set up a stake at *A* (100 feet away or more) so that it appears in the center of the field of view of the telescope. Now set up stake *B* exactly in line with *A* and *C* (middle of tube), revolve the tube about its declination

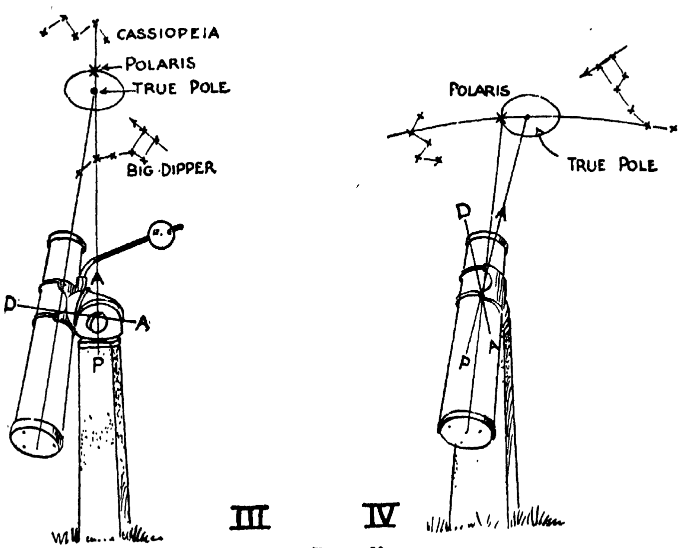


FIGURE 39

axis and see whether stake *B* is also in the center of the field. If it is not, shift the tube in its saddle by inserting shims at *E* or *F* until the image of stake *B* has moved back toward the center one-half its distance from the center. Then bring it exactly to the center by adjusting the mirror cell at the end of the tube.

Revolve the tube again, bring *A* into the center of the field (if it is not already so) by moving the entire mounting on the pier, and repeat the procedure until the two stakes appear in the field center. If they are, it is a proof that the mirror axis and declination axis are at right angles to each other.

Were Polaris (the north star) a little nearer the celestial pole (that point in the heavens where the axis of the Earth, if prolonged, would intersect with the background of the stars), we would be able to see the star in the telescope off to one side if the true pole were at the center of the field. But it is actually a little over a degree from the true pole and the field of a low power eyepiece is only about half a degree in diameter, so we must perform the adjustment in two stages shown in Figure 39, and this method applies to all telescopes, whether refractors or reflectors.

We can make the first adjustment when Polaris is above or below the pole (shown at III as just above the pole). Polaris will be above the pole when the constellation resembling a capital M or W (known as Cassiopeia) and the Big Dipper are in the positions shown in the figure. A line drawn between the star at the break in the handle of the Dipper, and the one indicated in Cassiopeia, passes almost exactly through Polaris and must be about vertical when the adjustment is made.

With the tube as shown; that is, with the declination axis horizontal (the tube may be on either side of the pier), move the whole mounting on the base plate until Polaris is picked up in the eyepiece and brought to the center of the field. (Remember, the declination axis itself is not to be disturbed; the whole mounting must be moved by turning it on the bolt imbedded in the pier, and by elevating or depressing the tube.)

Six hours later or earlier (later as shown in IV of Figure 39) Polaris will have moved round in its orbit until it is at the same altitude as the true pole, that is, just west of it. Revolve the tube until the declination axis is in a vertical plane. The telescope will then be over the pier and can sweep from east to west. The tube is then depressed by adjusting the entire mounting with the base-adjusting screws until Polaris comes to the center of the field. While doing this, do not allow the mounting to turn horizontally, as this would disturb the first adjustment.

The lock nut on the central pier bolt is then screwed home.

There remains the location of the indexes, or points from which the circles are read. On a later evening, with Polaris above the pole, the declination index line or pointer should be placed or marked opposite the circle reading 89 degrees; and since Polaris is then directly north of the observer, it is in the observer's meridian, and therefore the hour angle is zero. The hour circle index should therefore be placed opposite zero on the hour circle.

CHAPTER VI.

Finding Celestial Objects. Star Time

Astronomers have covered the heavens with a net work of imaginary lines, very much as we cover the earth with circles of latitude and longitude, the only difference being that we are outside these lines on the Earth, but are inside and looking out at the celestial net work. The names they give these lines are also different. Instead of latitude they say "declination," and the term "right ascension" takes the place of Earth longitudes. Where we would fix New York on the Earth as in Lat. 42° north, Long. 5 hours west, they would locate a star as in Dec. 42° north, and R.A. (right ascension) 5 hours; and so, since it is customary to look down on Earth objects from outside, as in I, Figure 40, we must accustom ourselves to gazing out from the Earth's center (as inside an umbrella, V) and seeing the star located as in II.

Astronomers select a certain point in the heavens from which to reckon their right ascensions, just as we agree in reckoning longitudes from a spot on the Earth's surface; viz: Greenwich, England. Moreover, instead of going 12 hours each way from their Greenwich as we do on the Earth, they keep on clear around the heavens from zero to 24 hours. The diagram shown in II would represent a portion of the sky to an observer looking south. The northern heavens might be represented somewhat like III. To lend the sense of perspective, the circles of declination are shown as ellipses instead of circles as is actually the case.

It will be noted that as one faces the south (II) the hours of right ascension increase towards the east, but that the stars (due to the Earth's turning over) appear to move in the opposite direction—west—as shown by the arrow. On the other hand, if one looks north, while the hours increase toward the east over the pole, below the pole right ascension increases toward the west and the stars in this region are apparently moving eastward (III).

The difficulty of visualizing these motions and directions lies, of course, in trying to depict on a piece of flat paper what exists on the inside of a hollow sphere. Only by continued use of the telescope and star charts will one become familiar with the heavens and sense the structure of its reference lines.

One other subject needs to be considered before trying to pick up a celestial object with the telescope; viz.: star time. If we imagine a vertical plane passing through the observer and the north pole, it will produce the line *AB* in II on the sky, and be referred to as the "meridian." As shown in the figure, if a star had the right ascension of 1½ hours it would be just crossing this meridian line and star time would be 1:30 (as indicated on the watch dial). In other words, star time *is* the right ascension of the meridian, whatever the particular R.A. happens to be at the moment. The star shown, having a R.A. of 5 hours, will not cross the meridian for 3½ hours, and (when it does) the watch will then be reading 5 o'clock. This particular star in the position indicated in II has an hour angle of 3½ hours east. Hour angles are somewhat as shown in IV, where a solid hour angle is shown cut out of a

sphere, very much like a piece of an orange. If the star to be found is west of the meridian, it has a west hour angle.

Since right ascension increases from 0 to 24 hours, like the time tables on some of the European railroads, ordinary watch dials reading from 0 to 12 hours can be used only by remembering that when star time has passed 12 hours, 13 hours will be indicated by 1 o'clock on the watch; 14 hours as 2 o'clock; and so on up to 24 hours. Dials reading from 0 to 24 may, however,

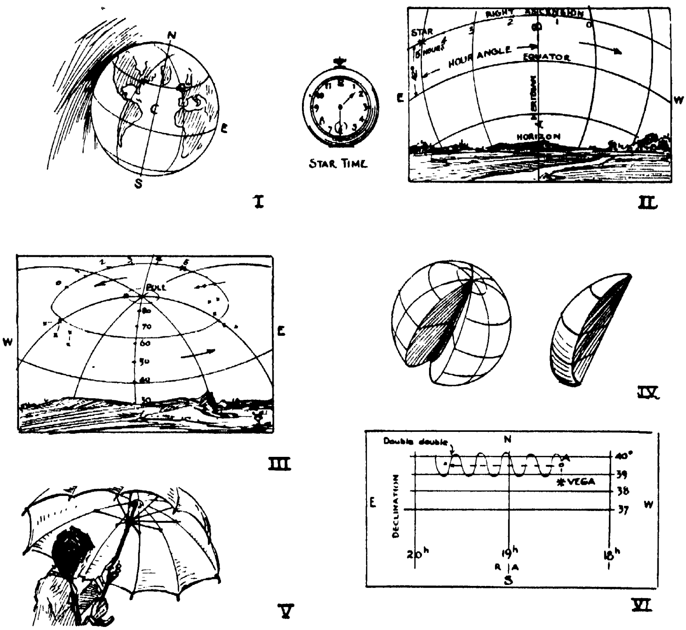


FIGURE 40

be obtained. Sometimes they are shown with the hours from 12 to 24 placed inside those reading from 0 to 12.

Several good books are available giving descriptions of interesting celestial objects along with their declinations and right ascensions. Ball's "Popular Guide to the Heavens" is one of them; Webb's "Celestial Objects for Common Telescopes" is another.

The American Ephemeris and Nautical Almanac gives the places of all the objects of the solar system and a great many of the brighter stars. The

watch is first set running on star time, by waiting until some bright, easily identified star approaches the meridian. At the moment it reaches the center of the field of view of the telescope, set the watch to the star's right ascension, remembering that if the star's R.A. exceeds 12 hours, 12 hours must be subtracted from it.

Let us take for our first object some bright star, such as Vega in Lyra, which in mid-summer will be found crossing our meridian almost overhead. Vega is so easily identified that any blunder occurring in our calculations tending to point the telescope off into another part of the sky, will become immediately apparent. Its position in the heavens will be found to be: Dec. 38° 42′ north; R.A. 18 hours 34 minutes, and the star's declination is directly set off on the declination circle of the mounting.

If it happens to be about 8 o'clock (civil time) on an evening in August, the watch (star time) will show, say, 17 hours 30 minutes. This means that all stars with this R.A. are on the meridian, and since Vega's R.A. is greater than this, also since right ascensions increase as you go into the east, then the star's hour angle will be:

18h	34m
17	30
1h	4m

east of the meridian. Therefore we move the tube over into the east (about the polar axis) until the hour circle reads 1 hour and 4 minutes. Vega ought then to be somewhere near the center of the field of view in the telescope.

Later in the evening, say about 10 o'clock, with the watch reading 19h 30m Vega will have crossed the meridian and its hour angle will be west, and equal to:

Watch	19h 30m
Star's R.A.	18 34
	0h 56m

which is the setting to be made on the hour circle, the telescope tube now pointing somewhat to the west of the zenith.

Another good object to experiment on is the Moon, or any of the brighter planets. If in the daytime, we have our Sun (which is a star relatively near us) whose position in the heavens is given in the Ephemeris for every day of the year.

In this way, that is, by using the setting circles, many fascinating nebulae, star clusters, colored doubles, may be found and studied that are entirely invisible to the naked eye.

With mountings not provided with setting circles obscure objects may be located by first picking up a nearby bright star and then by two separate steps working toward the region occupied by the object in question. For example, close to Vega there is a very interesting test object, *Epsilon Lyrae*, made up of two faint stars just visible to the naked eye, each one of which is a double star. As we look up at Vega, facing south, this double double will appear in relation to Vega as in VI, though it is impossible on the small scale employed in the drawing to show separately the individuals of the pairs.

The differences in declination and R.A. between Vega and the double double are, respectively, 0° 50′ and 0h 6m, so if the tube is moved north about 1° (estimated) in declination, and then swept east in R.A., the double double will very likely come into view. There is no mistaking it when once located—two pairs of twin suns, each pair separated by only a few seconds of arc. If not found at the first try, go back to Vega and repeat the steps, perhaps moving the tube as shown, back and forth in declination as it is slowly advanced in R.A., thus sweeping over a larger area of the sky.

A HOME MADE TELESCOPE

Twelve inch mirror. Axes made from two Ford axles. The materials in the tube cost two dollars. Made by John Roney and described in Scientific American, October, 1926, page 298.

CHAPTER VII.

Telescope Housings—the Warmed Observing Room

The time honored manner of enclosing a telescope permanently mounted on its pier is by means of the hemispherical dome revolving on a circular track. A slit in the dome allows any part of the heavens to be reached with a minimum of exposure of the observer to the weather. All large telescopes are housed in this way, but these domes are expensive and difficult to make and are hardly needed for the relatively small instrument of the amateur.

It may be of interest to know what has been accomplished in the way of providing the star gazer with a closed and warmed observing room entirely independent of outside temperature. So far, in order to accomplish this end, an additional reflection has been needed in order to bring the image into the room and still preserve the principle of the equatorial mounting.

In Figure 41 are several schematic diagrams showing how the problem has been solved for refractors. In each case the mountings are meridianal sections

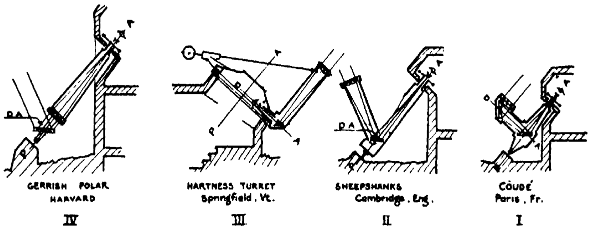


FIGURE 41

in the plane of the paper, and the polar and declination axes are lettered *PA* and *DA*, respectively. All of these types have been built and are in daily use. In I, II and IV the observer looks down the polar axis through a fixed eyepiece. In III one looks down the declination axis and the eyepiece describes a small arc of 180 degrees in covering the heavens. I and III take in the entire heavens. II and IV are cut off from part of the northern sky.

In reflectors the relations of the primary and eyepiece, with respect to the object viewed, are reversed, thus changing the problem. So far as is known, only one or two attempts to adopt the Newtonian silvered glass telescope to an enclosed observing room have been made. I used the arrangement shown at V, Figure 42, in my former home on the Maine coast for several years, but it is now dismantled. It is not recommended on account of the inconvenience of looking up the polar axis. This becomes very trying to the neck muscles after long periods of observing. This mounting was described in *Popular Astronomy,* in 1917, and the description was reprinted in the *Scientific American Supplement* for August 4, 1917.

Mounting VI, a photograph of which is shown elsewhere, is at *Stellafane,*

Springfield, Vermont. The turret carries two telescopes, a 16-inch Newtonian of 17 feet focal length, and a Cassegrainian 12-inch of 16 feet equivalent focal length, so that two observers may study the same object simultaneously.

Mounting VII might be called a polar Cassegrainian. It is just being built now at "Stellafane." And VIII, so far as I know, has never been built.

Mountings V and VII leave parts of the northern heavens obscured; VI and VIII are universal.

The upper telescope of VI demonstrates that it is possible to bring the focus of a mirror into a room without an additional reflection. I have shown

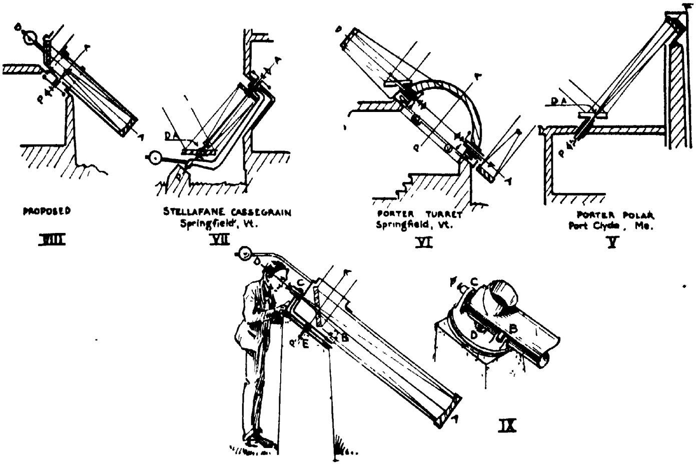


FIGURE 42

the arrangement again in IX in another position and adapted to a pier out of doors. The prism is replaced by a large flat mirror with a hole at its center. The tube carrying the two mirrors revolves in declination on the two rolls *B* and hollow bearing *C*. These supports are carried on the circular plate *D* which in turn revolves in right ascension on the stud *E*. The difficulty involved in perfecting this train of optical parts is in the perforated flat; cutting out the central hole after the mirror has been figured, results in a raised rim about the hole, due to released strains in the glass. If it is attempted at all, the central core should first be cut out and then replaced, cementing it to the glass with plaster of Paris. The whole is then fine-ground, polished and figured, and the central core is removed afterward. The perforated mirror must be very flat, otherwise any slight departures from a plane will seriously affect the image, due to the fact that it is outside of the concave mirror.

CHAPTER VIII.

The Prism or Diagonal

The essential part of the diagonal is an optically flat surface of glass placed at an angle of 45 degrees with the axis of the mirror, in order to throw the reflected cone of light from the mirror out at one side where the image formed at the focus can be viewed with an eyepiece.

This reflection may be produced in one of two ways—either by the use of a right angled prism, I, Figure 44, which will totally reflect the rays as shown, or by a piece of plate glass silvered on the side facing the mirror. The advantage of the prism over the silvered diagonal is that it requires no silvering, but an inch prism such as will be required for a 5-inch mirror costs about six dollars, and perhaps the amateur would prefer to silver his own diagonal and put the six dollars into an eyepiece.

The glass for a silvered diagonal can be obtained from a piece of broken wind shield or thick plate looking glass. We want to select as flat a portion as possible, so we get a glass cutter and cut the sheet up into several pieces each about 1¼ by 2 inches.

Clean the glass thoroughly, select two pieces, free them from lint or dust and press them together. To bring them into close contact, slide or wring one piece on to the other, using considerable pressure. If they are now held so as to reflect light from a bright area—say the sky—colored bands, or fringes, will be seen, and these will appear to be located on the two surfaces in contact. By squeezing the pieces together near the edges these colored bands may be made to move about or change their form.

Not over half a dozen bands can be seen by sunlight or artificial light, but if a little salt is thrown on the wick of an alcohol lamp, as in Figure 43, the very yellow resulting flame will show many more bands, alternating black and yellow. This must be done in a darkened room.

The shape of these bands, or fringes, tells us the kind of surfaces that are in contact—whether they are convex, concave, warped or flat. The bull's-eye in the pattern at *A*, in II, Figure 44, can be moved off the glass and given a pattern like *B* by pressing the glass together at *a*. By pressing still harder at *a*, fringes will begin crowding in from the opposite side of the glass, and the bands themselves will grow narrower *(C)*. With the salt flame hundreds of these fringes may be seen until they become so fine and close together as to pass beyond the resolving power of the naked eye. This crowding in of the fringes on the opposite side from *a*, means that the surfaces are opening out on the left side, and if the pressure is moved over toward *b*, the bands will move off to the left until there are only a few left. By varying the pressure, the wedge of air existing between the two plates may be made to take any desired direction, and if the plates are convex or concave to each other, the center (or bull's-eye) of the fringe system may be made to come into view by appropriate squeezing.

What interests us is the fact that these bands may be regarded exactly like contour lines on a map. If we laid plate *A* on what was known to be

a perfectly flat glass, then anywhere along fringe 1 is half a wave length, or 1/100,000 of an inch, above or below any part of the glass along fringe 2; and 2/100,000 of an inch above or below fringe 3, depending on whether the surface of plate *A* is concave or convex. If the rings spread out on lowering the eye the plate is convex; if they close together, it is concave.

However, we have no standard flat, so we must go at it another way. A departure from flatness of one wave length of light may be tolerated, and since this means two rings, if three different pieces of glass laid one upon the other show no more than two rings, then any one of the three will answer. They must be tried No. 1 on No. 2, 2 on 3 and 3 on 1. Pick out one of a pair of plates that shows the straightest fringes.

The diagonal is so near the eyepiece that any deviation from absolute

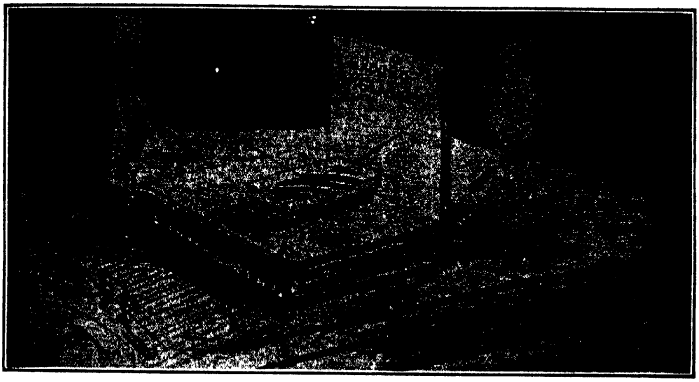


FIGURE 43

flatness amounting to less than 1/50,000 of an inch will not harm the image produced by the mirror.

The corners of the plate may finally be cut off as in II, at bottom, and the edge ground down with No. 200 carborundum on a slab of iron or glass into the ellipse shown. Silvering should be done as described in the section on silvering the mirror, and on the face of the diagonal.

While a piece of commercial plate glass sufficiently flat to serve our purpose can usually be found, one can purchase a prism blank from the Spencer Lens Company of Buffalo or the Bausch & Lomb Optical Company of Rochester, New York, for less than a dollar and grind and polish it one's self. The prism blank is first rough ground to the approximate shape, then carefully fine ground until it fits the proper templates (III). The prism is then laid, hypothenuse face down, on a slab of plate glass *D* (broken wind shield) as in IV, and four pieces of wind shield glass are laid around it as shown, cut so

as to form with the prism a roughly circular surface. The end of a tin coffee or baking powder can *(A)* is then laid over the glass, the edge of the can resting on matches *(B)*. The hole *C* has previously been cut from the end of the can. Plaster of Paris is then poured into the hole and when set, the whole affair may be slid off the slab *D* and turned over. Cut away the plaster so that the glass will be raised above its surface an eighth of an inch, and when the plaster has thoroughly dried, coat it with hot beeswax.

The exposed prism and four glass pieces are now to be fine ground on a

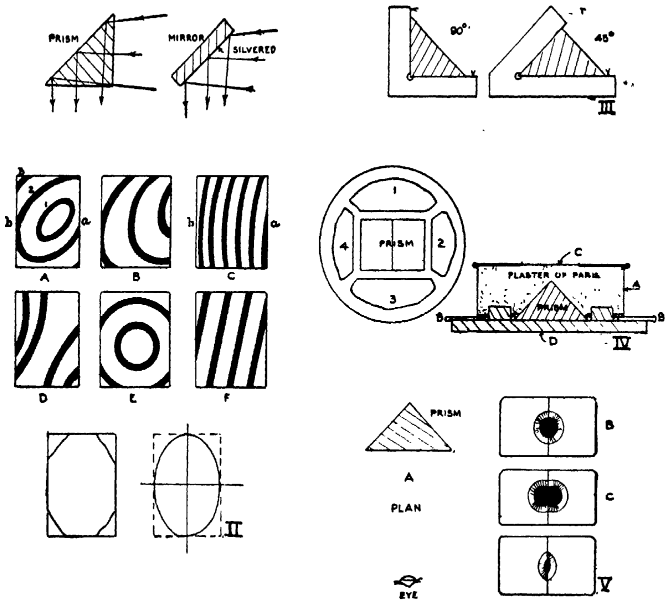


FIGURE 44

slab of plate glass and the units polished as though it were a whole disk, just as the mirror was polished.

After polishing, the prism is broken away from the plaster, turned over on one of its square faces and the operation is repeated. The other square face is likewise polished, and then the prism is finished.

The right angle of the prism need not be exactly 90 degrees for our purpose. To find out whether it is 90 degrees, the worker should hold the prism in front of one eye, about a foot away, with the hypothenuse face facing him

and its longest sides horizontal, as in V, *A*. In the prism will be seen the reflection of the pupil of the eye as in *B*, perfectly round if the angle is 90 degrees, but elongated if the angle is less than 90 degrees as in *C*, and drawn together if the angle is more. The displacement is increased as the prism is moved farther from the eye.

Now for a useful application of algebra. Pick out any three pieces of glass and label them *A*, *B* and *C*. Let us assume that *A* on *B* gives the fringes shown in I, Figure 45, and show three fringes convex:

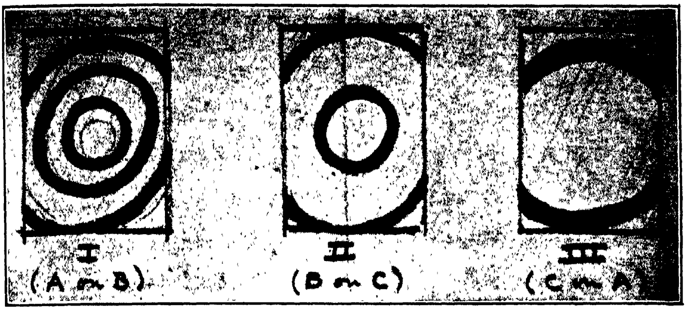


FIGURE 45

Also that *B* on *C* gives two fringes concave, and that *C* on *A* gives one fringe convex. This gives us three simultaneous equations. Then, letting the plus sign denote convexity and the minus sign concavity—

$$\begin{aligned} A + B &= +3 \\ B + C &= -2 \\ C + A &= +1 \end{aligned}$$

Removing *B* from the first two equations, by subtraction,

$$\begin{aligned} A + B &= +3 \\ B + C &= -2 \\ \hline A - C &= +5 \end{aligned}$$

Combining this with the third and solving for *A*,

$$\begin{aligned} A - C &= +5 \\ C + A &= +1 \\ \hline 2A &= +6 \\ A &= +3 \end{aligned}$$

Substituting this value of *A* in the first equation,

$$\begin{aligned} 3 + B &= +3 \\ B &= 0 \end{aligned}$$

And substituting this value of B in the second equation,

$$0 + C = -2$$
$$C = -2$$

Since one fringe of yellow light is 1/100,000 of an inch, this tells us directly that piece A is three fringes $\left(\frac{3}{100{,}000} \text{ of an inch}\right)$ convex, B is flat, and C two fringes concave.

We can in this manner, with only an alcohol lamp, and without recourse to any expensive master flat or involved mathematics, know how flat a piece of glass is almost to a millionth of an inch.

If one of these pieces of glass were to be increased in size until it was a mile long, a millionth of an inch error in its surface would show up as a bulge or depression only one-fourth of an inch high—or deep.

A HOME MADE TELESCOPE

A four-inch reflector made by Frank Murray and described in Scientific American, July, 1928, page 74. Total cost under twenty-five dollars. Focal length 30 inches. Tube consists of six cypress slats screwed to a hexagonal block of wood at bottom, and bolted to an iron ring at top. Altazimuth mounting.

CHAPTER IX.

Optical Flats

Since plane mirrors are a part of reflecting telescopes where silvered diagonals are used in place of prisms, and as aids in testing both the concave at its focus as well as the two mirrors of the Cassegrainian, an account of the technique employed in making flats will be of interest to the amateur.

There are three methods of producing a true plane, each of which will be described. The first follows the time honored process of making metal surface plates of the kind so extensively used in the machine tool industry, and rests on the fact that if any three surfaces are found to be in complete contact where tried in all possible combinations, they must all of them be plane; they cannot be otherwise.

In machine shop practice the cast iron plates are rubbed on each other and the high spots scraped off until all three plates touch everywhere—say at least in half a dozen spots to every square inch. We cannot do this scraping operation on glass, and must pursue the slower and more arduous method of altering each surface as a whole on a bed or lap of pitch in very much the same way as the paraboloidal mirror is figured.

Starting, then, with three (say six inch) disks of plate glass one inch thick, each one numbered for identification, and laid out on the table, we begin by fine grinding 1 on 2, then 2 on 3, then 3 on 1, going over this sequence time and time again until it is assumed that all three are flat. Of course there is no knowing when this condition is reached until they are sufficiently polished to test by interference, but starting with commercial plate glass surfaces, two or three hours fine grinding should suffice.

The surfaces, to start with, are all flat to at least a thousandth of an inch and only No. 600 carborundum or No. 906 emery need be used. Toward the close of the cycle it is best to shorten the time of the individual wets, for if carried too long the tendency of the upper disk to go concave and the lower convex will be appreciable.

The next step is to prepare a normal pitch lap, forming it while it cools with any one of the three disks, and then giving each disk about ten minutes polishing, or sufficient to observe the interference fringes when two of the surfaces are laid in contact. (The reader should now refer to Chapter VIII, on "The Prism or Diagonal", for the manner in which these fringes are produced and interpreted). If the fine grinding has been carefully carried out, only one or two fringes will be seen and these will be in the form of perfect rings or circles like the rings around the bull's-eye of a target. (See *b* and *c* in Figure 46).

Since we must look through the disks to study these fringes, handles can not be pitched on to their backs. The grinding and polishing must be done by the hands alone.

Suppose that after solving the equations described in the last chapter, disk 1 comes out convex, it can be flattened by reducing the size of the facets of the lap uniformly from center to edge, as in *a*; or even by working over the normal lap the upper member will tend to go concave.

Should disk 2 be concave, modify the lap in an opposite manner to that shown in *a*—that is, with facets increasing in size from center to edge. Or use a normal lap on top with the disk below.

Disk 3 may be neither convex, concave nor flat, but of a real section shown in Figure 47, like the apparent section of the paraboloid at its mean center of curvature. Here we must wear away zone *x*, and I have found that the

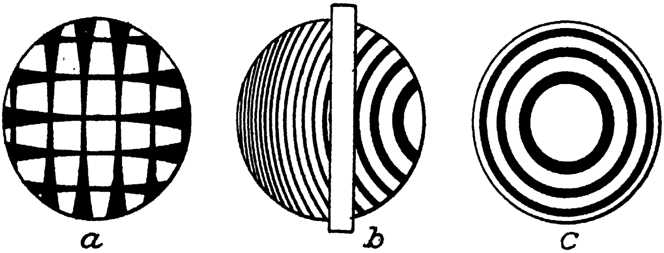


FIGURE 46

best form of lap is in the shape of a ring of pitch shown in section over the disk section in the same figure. The action of this ring, and the character of the stroke used, are identical with those involved in figuring the small convex mirror of the Cassegrain, and described in Chapter X.

During the figuring of these near flat surfaces, they should be tested frequently by interference and new equations formed. The latter method tells faithfully at any stage of the work the relationship of each surface to the theoretical plane.

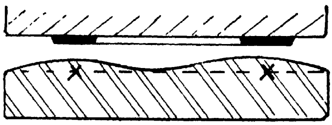


FIGURE 47

The approach to perfection can be carried as far as the worker's patience will permit, though flat to 1/100,000 of an inch is doing pretty well.

It is interesting to note that the fringes can be interpreted in two different ways: one by bringing the center of the fringe system (or bull's-eye) into the center of the disk and counting the number of rings visible; the other by laying a straight-edge across the glass and counting the number of fringes it cuts across. Thus, in Figure 46 are shown two positions of the fringe system produced by the same surfaces, the one at *c* having the bull's-eye central when

three rings can be counted, and the one at *b* showing the center well off the disk. Here, also, the straight-edge cuts through three segments of rings, giving the same result. These rings are strictly analagous to contour lines on a map.

The time required to produce a six-inch flat—say, flat to 1/100,000—by the above method, is roughly the same as making a paraboloidal mirror. Of course, only one of the three disks need be brought to a complete polish.

Care must be taken to avoid scratches when these disks are laid together for testing by interference. Rubbing one on the other to bring them together will almost surely develop a scratch. If the fringes do not appear at once on contact, separate the disks and clean each surface again. It takes only a small

FIGURE 48—FLATS

The one on the left is ten and one-half inches in diameter, one and one-half inch thick, and is one of three made of fused quartz produced at the Thomson Laboratory of the General Electric Company, Lynn, Mass. The work of polishing and figuring was performed by John Clacey of the United States Bureau of Standards Optical Shop, in Washington, using a pitch lap three eighths inch thick. The testing was done by C. G. Peters of the same institution. The flat is accurate to one-hundredth of a wave-length or 0.0000002 inch, despite the curved fringes, which are almost wholly the result of slanting viewpoint, as explained in Scientific Paper 436, B. S., "Interference Methods for Standardizing and Testing Precision Gage Blocks" (Govt. Printing Office, Wash., D. C., 10 cents). Also see editor's note at end of chapter. The flat shown on the right was made by Russell W. Porter and is the one referred to in the present chapter. Diameter 10 inches. The turned down edge has not been ground away or cropped out in reproducing the photograph.

particle of dust or lint between them to prevent the fringes from appearing. The palm of the hand is the best wiper to free the glass of adhering particles.

Of course, the same care must be observed in letting the disks return to a uniform temperature before testing, as is required in testing the paraboloid.

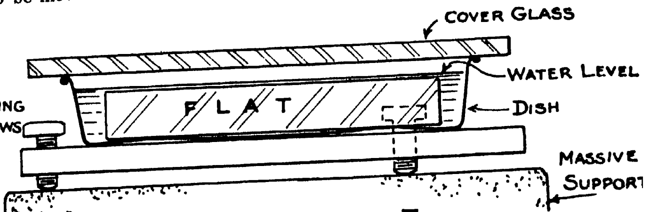
I recently figured three 10-inch disks until they all departed from flatness less than one-quarter of a wave-length of light. I photographed the fringes

from two of them in the light of a mercury vapor lamp. One is shown in Figure 48, at the right. There is a turned down edge of half a wave (1/100,000 inch). The time required was one solid month of intensive application.

The second method of making a flat and the one more likely to be tried by the amateur, since it requires but one disk of glass, is that in which the knife-edge is used in conjunction with the concave mirror of the telescope while the mirror is still spherical and before it is parabolized.

The silvered concave is set up on edge as shown in Chapter III, Figure 33, and the flat is interposed at about 45 degrees, so that the eye sees the concave mirror by reflection in the flat as though it were at *B*. If the flat is truly plane the knife-edge shadow will be of the uniformly grey appearance characteristic of a spherical surface (as described in Chapter I, Figure 11) whether the knife-edge comes in from the left or down from above.

But if the knife-edge is in one position when coming in from the left, and has to be moved in towards the mirror when cutting in from above (in order



THE RALEIGH WATER TEST FOR FLATNESS

FIGURE 49

to produce uniform illumination), then the flat is convex. If it is concave the reverse is the case, that is, the position of the knife-edge from above is farther from the mirror than where the knife came in from the left. This phenomenon is caused by the foreshortening effect due to the diagonal position of the flat.

The sensitiveness of the knife-edge test, as compared to that of interference is roughly of the same order, at least to the extent that the amateur is likel to carry the refinements of either method.

The third method assumes that the workman can borrow an optical flat an use it for a master with which to make his own. He will fine grind his disk a flat as possible, testing it with the best straight-edge he can get hold of, brin it to a partial polish, lay it on the master and observe the fringes. If they ar straight his glass is flat, no matter how close the fringes are together—his on criterion for flatness is that the fringes are straight. Of course they may b separated at will to any desired distance apart by altering the wedge of a between the disks. I usually separate the fringes about an inch apart whe testing, but it is an arbitrary choice. As the air is slowly excluded and tl

air wedge decreases, the fringes disappear one by one, off the thicker end of the wedge until, as the last fringe widens to the diameter of the disk, the glass is covered by one complete fringe (center at infinity), of one color, which in the case of the sodium flame (common salt), is yellow.

Theoretically we all have access to a perfectly flat surface for testing purposes simply by filling a dish with any transparent fluid and immersing our disk in it. This is known as the Raleigh Test, and is curiously intriguing from its very simplicity.

Set a basin on a firm and massive support having three adjusting screws, as in Figure 49. Place the flat in the basin and pour in water until the glass is covered by a water film about one-sixteenth inch thick. Over the basin place a sheet of glass, to exclude air currents. Now level up the glass by observing the reflections from some sharply defined point in the room, such as a lamp filament. There will be two reflections of each object from the two surfaces—air-water and water-glass. When the double reflections merge into one another the surfaces approach parallelism, and (if one's patience holds out) interference fringes will form on the glass. Of course, some source of monochromatic light must be used to illuminate the glass, such as the alcohol lamp saturated with salt.

This test sounds easy, but is far, far from it. With the slightest tremor of the water surface the fringes are gone. In using this test in the basement of my former home in Newton, Massachusetts, the arrival of a train at the station half a mile away was enough to destroy the fringes. I have never yet heard of a person making an optical flat by using a water surface as his reference plane.

It is interesting to note that a 200-inch mirror, if given this water test, even were it actually flat, would appear two fringes concave, from the curvature of the water surface, due to the curvature of the earth!

One might well try making his first flats by the first method described, with small disks, say of two inches diameter and a half inch thick. They are very useful in checking up the flatness of prism faces, the flat sides of lenses and in selecting pieces of plate glass for diagonals for telescopes. If one is a mechanic he can by means of them check the flatness of the anvils of his micrometer and the wear on his gauge blocks.

[Editor's Note: As stated beneath Figure 48, slanting vision introduces inaccuracies into the estimation of the fringes on a flat. The following comment by C. G. Peters, Chief of the Interferometry Section, Bureau of Standards, will suffice for average conditions: "For a practical test, where an accuracy of not more than one-tenth wave-length is desired, view the fringes with the eye as near as possible on the normal to the center of the surface. Have the distance from the eye to the surface at least four times the diameter of the plate. Under these conditions the error made is less than one percent of the thickness of the air film between the plates. If this distance is, say, 10 wave-lengths, the error made is less than 0.1 wave-length. From this it is evident that, the farther the eye is moved away from the plate, and the smaller the distance between the two plates, the more accurate the test becomes."]

CHAPTER X.

How to Make a Cassegrainian

(And Why Not To)

There is something in the make-up of the Cassegrainian reflector to whet the curiosity of the amateur, intriguing him with a strong desire to construct a telescope of this type. In the first place, he argues, the addition of a small convex mirror of negligible size will quadruple the power of his instrument, or reduce the length of his tube to a quarter of what he would require in the Newtonian form of equal focal length. Then, too, he argues, you are looking straight toward the object being observed, as in the refractor, and not in at the side where the reflection of the diagonal perverts the image.

While all this is true, the amateur fails to appreciate the fact that the addition of each optical surface complicates his troubles, and that he must figure a flat mirror for testing purposes, at least as large as his paraboloid. This alone doubles or trebles the work. Furthermore, his telescope will be worthless in the daytime for looking about the country, on account of extrane-

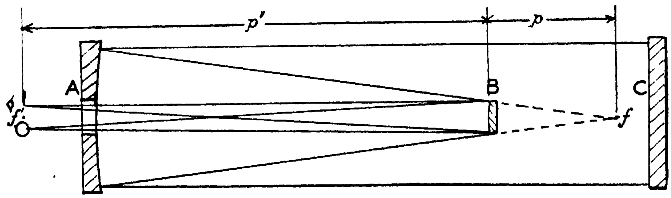


FIGURE 50

ous light fogging the field of his eyepiece. We might look at it this way: This stray light reaching the eyepiece from around the small convex mirror could be completely cut off by lengthening the tube to four times the focal length of the primary. But there is nothing to be gained here over a Newtonian of similar length and power. Of course, a diaphragm stop could be used.

However, I shall describe how the Cassegrainian combination is produced, hoping, nevertheless, that the beginner in glass working will weigh carefully the desirability of attempting one, at least until he had made several telescopes of the simpler kind.

The paraboloid *A*, Figure 50, needs no explanation to one who has made a Newtonian telescope, as it is identical with the mirror of that type, except that it has a hole at its center to permit the converging light from the small convex mirror *B* to reach the eyepiece and observer at f'. If the concave is made in the usual manner and the hole is cut out afterward, a miniature crater will spring up around the orifice, due to strains being relieved in the

plate glass which is not completely annealed, and it is almost impossible to remove this raised zone by local polishing without getting a turned down edge around the hole. To obviate this it is better, just before fine grinding, to cut out the hole with the "biscuit cutter" and cement the glass core back in again with plaster of Paris, with the mirror and core resting on the glass tool while the plaster is setting. Then go on fine grinding, polish, and figure; finally knocking out the core.

The secondary B is a convex mirror placed inside the focus of the primary, at such a position in relation to A and f as to give the desired increase in magnification. In the large mirrors on the Pacific Coast the secondary is about one-quarter of the distance Af inside f.

The formula giving the radius r of the convex surface is as follows: (See Figure 50)

$$r=\frac{2\,pp'}{p'-p}$$

Thus, if the concave mirror has a focal length of 48 inches and it is desired to increase this four times, the convex mirror will be placed 48 inches from focus f' and 12 inches from the focus f; and substituting,

$$r=\frac{2\times 12\times 48}{48-12}=\frac{1152}{36}=32$$

With the radius given, the small mirror is ground and polished to an approximately spherical surface, and then figured in connection with A and the flat mirror C, by the knife-edge test, the set-up being, as shown in Figure 50, with pinhole and knife at f'. (The reader is referred to the chapter on making flats, for the necessary information for making mirror C.) Mirrors A and C are silvered. The three disks are lined up on edge on a bench in a darkened room, the light from the pinhole going first to B, then to A, then to C. From C it returns to the knife-edge in the reverse order. There are five reflections in all, hence the necessity for silvering A and C.

It will be noted that the returning light leaves C as a parallel beam, as though it came from a distant star, and the appearance of the knife-edge shadow (if all the mirrors are assumed perfect) should be that given by a spherical surface tested at its center of curvature; namely, the uniform gray of an apparent flat surface.

But the small convex surface will, at first testing, probably be about spherical, and the appearance of the shadow observed upon it will have the familiar appearance of a paraboloid at its center of curvature, with an apparent section as in Figure 47. The obvious procedure now is to wear away the apparent high zone at xx of the same figure, down to the apparent flat surface shown by the dotted line.

A ring lap, shown in section just over the apparent section of the mirror in Figure 47, will be found effective in reducing the zone xx, using straight strokes varying in length from zero to a point where the pitch ring reaches the edge of the mirror. This, in the writer's opinion, is the most difficult step in making the Cassegrainian, on account of the relatively small surface to be

worked upon locally.* For a 6-inch telescope the secondary will be less than 2 inches in diameter, and to deform such a small surface in the manner shown will be attended by many trials.

Another tool useful at this time is the "rose" tool whose action is a maximum at its center, decreasing to zero at its edge. This is shown superposed over the secondary in Figure 51, *a*. The stroke may be straight, with the path of the center of the tool tangential to the circle *x*; or elliptical with the center of the tool describing the path indicated at *b*, the intensity of shading in the loops shown representing the variation in pressure applied to each elliptical stroke.

If accidental zones are produced during this local figuring, they may be reduced by a return to a normal tool.

In testing the Cassegrainian in the laboratory with artificially produced

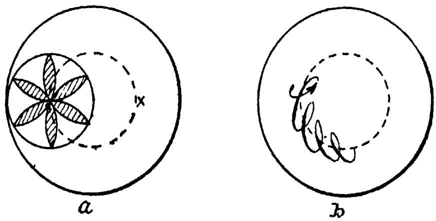


FIGURE 51

parallel light, the appearance of the pinhole image under an eyepiece will give as good (or better) definition as when the combination is used outdoors on the stars without the flat.

In lining up the three mirrors for testing, so that their axes coincide, adjustments must be provided for tilting the three surfaces.

The final surface figured on the convex mirror is said to be theoretically that of a hyperboloid.

In mounting the telescope tube provision must be made for the above adjustments, as well as a movement of the convex mirror toward or away from the concave, in order to bring the resulting focus to its proper place at the eyepiece.

Referring back again to the difficulty experienced in preventing a turned down edge around the hole of the concave mirror: when the 72-inch disk for the Dominion Astrophysical Observatory at Victoria was being figured by McDowell at Pittsburgh, this trouble was overcome by packing the hole with crushed ice. This resulted in a shrinking away of the glass around the rim of the hole, allowing the pitch lap to pass over the opening without unduly wearing down its edge.

I have made three reflectors of the Cassegrainian type, so far. None of them performs as well as my Newtonians of the same equivalent focus. The

reason the large mirrors on the Pacific Coast are used as Cassegrainians is not from any preference for that type of telescope, but rather that, to secure the focal length thus obtained would in the Newtonian form be prohibited by the cost and mechanical difficulties.

I realize that these rather negative recommendations of the amateur's Cassegrainian will not deter a lot of fellows from trying it out. The simple fact that I have stressed the difficulties will be enough to attract some temperaments—like forbidden fruit. Well—good luck.

A tube consisting half of sheet metal and half of openwork strips is the solution of the problem of air currents in the tube embodied in the telescope of Paul A. Chamberlain of North Tonawanda, N. Y.

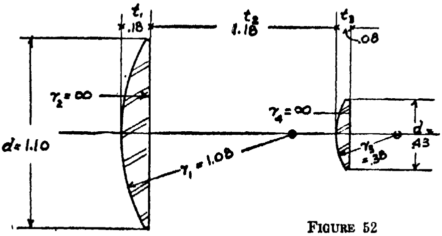
CHAPTER XI.

Making Eyepieces

The present chapter deals solely with the actual making of small lenses used in eyepieces, and the cells or containers in which they are assembled to make up the completed astronomical ocular.

The various types of eyepieces and the methods employed in testing them are covered ably by Dr. Hastings, elsewhere in this volume. I shall assume that the amateur has access to an ordinary lathe on which he may center his lenses, turn up his mount and the different laps required, and put together a simple vertical spindle similar to the one shown in the section on grinding machines, to be run by a small electric motor.

The glass blanks for eyepieces may be obtained from Donald Sharp, who carries the Chance Brothers (English) glass, or from the Bausch & Lomb Optical Co. All that is required of the amateur to secure his glass is to write to one of these firms, asking for blanks of the desired diameter and of the



RADII	THICKNESSES
$r_1 = 1.08$	$t_1 = .18$
$r_2 = \infty$	$t_2 = 1.18$
$r_3 = .38$	$t_3 = .08$
$r_4 = \infty$	

FIGURE 52

characteristics given, asking them to send glass disks having the constants nearest to these figures. Selecting, as an example, the Huyghenian ocular, the lens maker is interested only in the radii of their surfaces, the diameters and thicknesses of the components. The data are given in Figure 52. The specifications to be given the lens maker are in the table at the right. From these he constructs the drawing at the left, in order to determine the diameters of the blanks.

The field lens is first stuck to a small handle with hot sealing wax, as in *a,* Figure 53. A short section of piping or a cylinder of wood will serve as a handle. The blank is roughed to shape on any flat piece of metal or glass, to the form shown at *b,* and is then ready for grinding on the brass lap *c.*

The three laps employed have been turned up previously on the lathe and made to fit templates corresponding to the given radii. These templates are made in pairs, as at *d.* For each glass curve there should be two laps—one concave, the other convex. The reason for this is that they must be ground together in order to be sure of a truly spherical surface.

A convenient way to secure these laps to the spindle so that they may be

removed easily, will run true and not wobble, is to give the end of the spindle a taper and give the holes in the laps the same taper. The piece from which the lap is to be turned is first chucked in the lathe, as shown in *a*, Figure 54, and the hole and taper formed. The spindle itself is then chucked, the lap is driven on it and the curve is turned up with a hand tool (file) as at *b*.

The glass is now rough and fine ground on the spindle, working it across the revolving tool in short strokes, meanwhile turning it in the fingers very

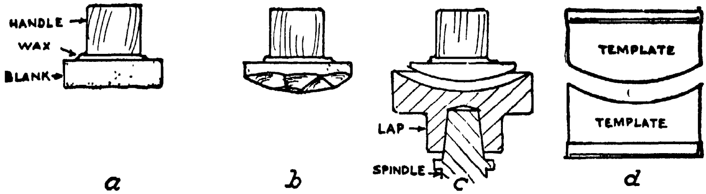


FIGURE 53

much as in grinding a paraboloid on a stationary glass tool. The speed of the lap for small lenses should be about 700 r.p.m., or roughly half that of the motor itself. A basin should be provided to catch the flying carborundum (see Figure 55, *a*). This can be made from an agate dish. A central hole permits it to be dropped down over the spindle and removed for cleaning.

If many lenses are to be made singly, they are often held by a pin in a bar, shown in *b*. The glass then takes up the motion of the lap and itself spins around, the worker moving the bar back and forth while he feeds on the

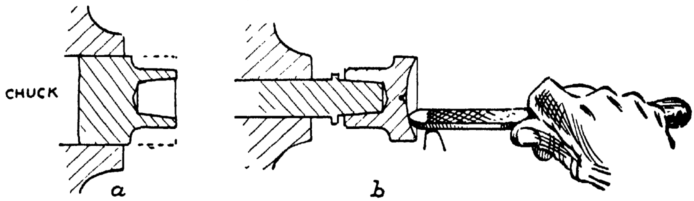


FIGURE 54

abrasive. A small metal wafer in which a shallow hole has been drilled to receive the end of the pin is pitched to the back of the glass blank. With this device the glass leaves the lap as a perfect surface of revolution, which will begin to polish evenly. But if ground by hand great care must be taken in the fine grinding to insure that the glass is in uniform contact on the lap. Where the curve of the lens is deep this spinning method cannot be used, as the point of application of the pin will be too far removed from the glass, and the lap will jerk the blank from the pin.

Where several lenses of the same kind are to be made, and the curves are not too deep, they may be combined in one unit as in Figure 56, *a* and *b*, by pitching them to the runner *A* and disposing them symmetrically in a group of seven around the central blank.

Brass laps wear out of true, and if used often should be ground together with their mates to preserve the spherical curve.

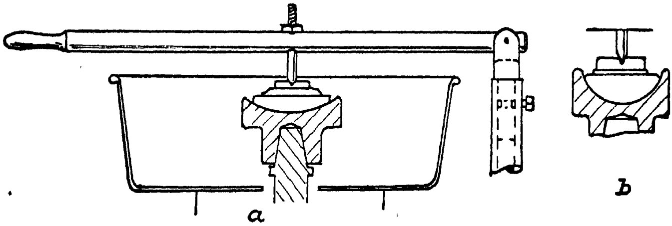


FIGURE 56

For polishing, the lap is cleaned, warmed and covered with about an eighth of an inch of hot pitch. Before it cools, the lap is placed on its spindle and formed to shape with the fine ground glass. With a sharp knife the edge is turned even and the central portion is removed, as in *c*. Heat will be generated by friction during polishing and the central hole will soon fill up. It must then be reformed.

Should polishing begin unevenly, go back to fine grinding. If it appears

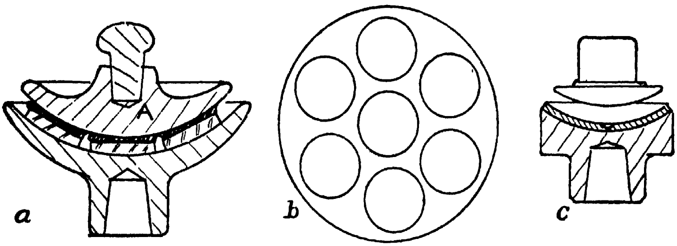


FIGURE 56

at the center, well and good—continue polishing until the polish reaches the edge of the glass, and all traces of pits have disappeared. This last inspection must be made under a magnifying glass, as the pits are too small to be seen with the unaided eye.

The glass is next warmed and the handle removed and pitched to the finished convex side, and the flat surface is ground and polished on a flat lap. The lens is then ready for centering.

The operation of centering consists of grinding down the edge of the lens, so that its optical axis is concentric with its edge. Lenses thus centered will have their axes coincident when they go into their cells assembled with the separating tube. If a lens is not properly centered we have the condition shown in Figure 57. An improperly centered lens is thicker on one side than the other. This amounts to a wedge *A* superposed on the lens, and when

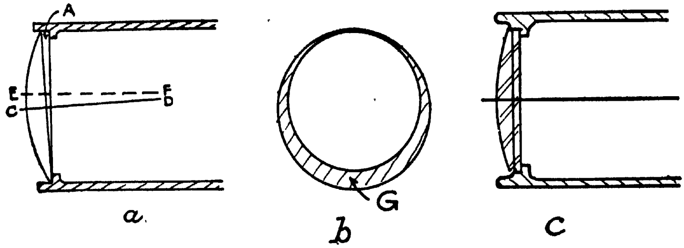


FIGURE 57

it goes into its mounting it will be lined up on axis *CD*, instead of the optical axis *EF*. The introduction of this wedge produces color, as might be expected, in the image. To correct the eccentricity the lens is rotated in the lathe in such a way as to grind away the area shown at *G*, leaving an edge concentric with the optical axis of the lens. This is accomplished in the following manner.

A piece of tubing slightly smaller than the lens is chucked in the lathe

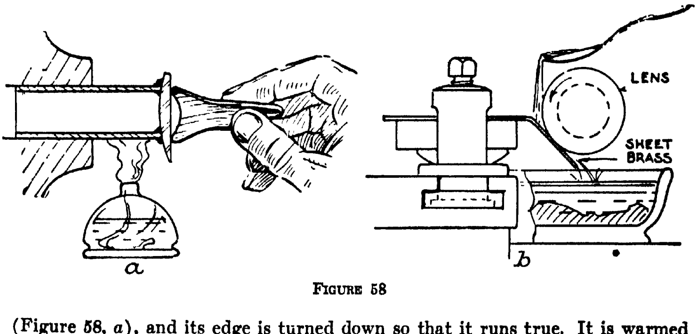


FIGURE 58

(Figure 58, *a*), and its edge is turned down so that it runs true. It is warmed by an alcohol lamp held beneath it. Sealing wax is daubed on its edge and the lens is pressed on until it bottoms against the edge of the tube. It is then rotated slowly. The glass is now seen to wobble in turning and any objects seen by reflection in the lens are not stationary, but revolve in circles. With the lamp in the left hand, warming the tube as in the drawing, a forked stick of

wood is pressed against the lens and as the wax softens, the glass will give automatically and run true. Objects reflected from it will then remain stationary.

The optical axis now coincides with that of the head stock spindle, and the edge of the lens may be turned down to the required diameter, which in our example calls for 1.10 inches.

I have never succeeded in satisfactorily turning down a lens with a diamond, probably because the glass must revolve at a very high speed, but it will readily respond to carborundum and water. A piece of sheet brass is held by the tool post and brought up to the glass, and about No. 220 carbo. is fed upon it with a spoon, as in *b*. The diameter is "miked" from time to time. Just before coming to size, shift to No. 600 carbo. Run the lathe at its highest speed.

After removing the finished lens from its tube (by heat) place it in alcohol over night to dissolve the sealing wax, for the lens is covered with carbo-

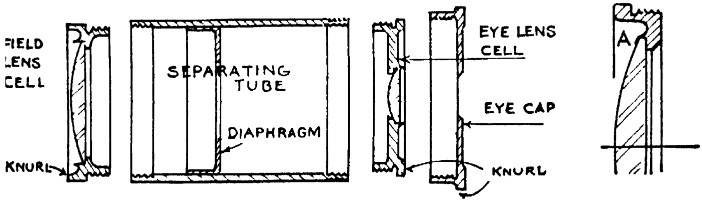


FIGURE 59

rundum and any attempt to remove the wax when it is hard will result in scratches.

The smaller or eye lens of the Huyghenian ocular passes through the identical operations required for the larger or field lens. We must now change to lathe work for the cells and separating tube.

The standard tube diameter for an astronomical eyepiece is an inch and a quarter. Stock for the separating tube may be purchased from Patterson Brothers or from Charles H. Besley & Co. It comes in just the right diameter and wall thickness, so the only operation here is to cut the tube to the required length and thread the two ends (internally) with a fine pitch thread, usually about 40 threads to the inch.

The cells (Figure 59) are turned and threaded from $1\frac{1}{4}$-inch solid bar stock. They are first threaded to fit the threads of the separating tube, and then cut off. One of these blanks is then screwed into the separating tube which is chucked so that it runs true, and the remainder of the cell is turned, leaving a recess a thousandth of an inch or so larger than the lens it is to accommodate.

The lens may be fastened in its cell with shellac or black sealing wax, or it may be crimped in by turning up a thin edge *A* and crimping it over against the glass with a small roller, running the lathe at its fastest speed.

If an eye cap is desired the eye end of the separating tube is threaded

externally and the cap is made as shown in the figure. Finally, the diaphragm is turned up and moved in the tube to such a position, by trial, that the edge of its aperture appears sharp when looking through the eyepiece. The diaphragm and inside of the tube are then painted a flat black.

The cells and cap are given a dark oxidized surface by immersing in nitrate of copper (dissolve some pieces of copper in nitric acid) and then heating in the oxidizing flame of a bunsen burner.

If a higher powered eyepiece is desired than the one here specified, all the quantities in the table are divided by such a factor as will give the desired increase in magnification. For example, an ocular of half the equivalent focal length (Fig. 52 is 1" *e.f.l.*) will be arrived at by dividing all the data by 2. This does not hold true when it comes to the mount, as the lenses diminish in size, while the outside diameter remains constant, viz., an inch and a quarter.

There is no short cut to a really good, efficient ocular. I know of no way of producing an eyepiece free from faults without access to a lathe, and in writing this chapter I have had in mind that group of young men who have an aptitude for this kind of work.

A HOME MADE TELESCOPE

Six inch mirror. Springfield mounting made up of two Ford front wheel assemblies secured at the auto wrecker's. Declination axis is a 1½ by 3-inch nipple, threaded from end to end, and has a Timken roller bearing from an old motor car. Pedestal is made of ¾-inch angle iron and light galvanized sheet metal fastened together with stove bolts, and is very rigid. Made by H. O. Bergstrom and described in Scientific American, December, 1927, page 555.

Part II.

THE AMATEUR'S TELESCOPE

By the Rev. William F. A. Ellison
M.A., B.D., F.R.A.S., F.R. Met. Soc., Director of Armagh Observatory, Member of the British Astronomical Association, and of the Société Astronomique de France.

CHAPTER I.

Introductory

Nearly 150 years have passed since William Herschel, then the unknown organist of Bath, began those experiments in telescope construction which in a few years made him the greatest astronomer and greatest master of the telescope that the world has yet seen. The Newtonian reflector was his chosen form of instrument almost of necessity. The achromatic lens was as yet in its infancy, and the Gregorian construction was too complicated for an experimenting amateur, and was, besides, only suitable for small sizes, and consequently limited in its possibilities.

A distinguished band of workers have, during the past century and a quarter, followed Herschel's lead, and nearly all have imitated his preference for the Newtonian, although the achromatic object-glass has become such a formidable rival to the concave mirror. The reason for the popularity of the Newtonian is still the same as in Herschel's day. It is the amateur's telescope, because, now, as then, it is the easiest to make and the easiest to mount, and far the cheapest either to make or to buy of any class of telescope. And, though cheap, it is not "cheap and nasty."

A good mirror is to the astronomer a thing of beauty and a joy for ever, capable of unfolding all the myriad glories of the heavens and of holding its own with the most costly products of the optician's art in definition and power. The names of those who have worked on it and helped to perfect it include many of the very brightest lights of the world of science in the nineteenth century. Lord Rosse, Lassell, With, Calver, Draper, Common, Foucault, Liebig, all gave of their best brains to the problems—most fascinating and alluring problems they are—set for solution by that beautiful sphinx, the paraboloidal mirror. That simple-looking disk of glass, with its almost imperceptible curve, shows little indication of the magical and mysterious powers which lie latent in it, powers to open to the astonished gaze a universe of glory and wonder; or of the amount of thought and anxious endeavor which have gone to the perfecting of its subtle curve and the depositing of its shining skin of silver.

Briefly, the advances since Herschel's time have been:—(1) The invention of the method of depositing a film of silver on glass by Liebig, improved later by Brashear and others, which made glass possible as a material for optical specula; and (2) Foucault's lamp and knife-edge, which made it possible for the workman to see exactly what he was doing while figuring the reflecting surface.

It was unfortunate that Foucault's test was not known to With. Had it

been, it would have immensely increased that great master's output, and also improved the quality of his work. As it was, Calver, though little, if at all, With's superior in skill, reaped the harvest of accuracy which With just failed to gather in. Many of With's specula have been retouched, to their great benefit, both by him and by the present writer, though one always handles a With mirror with reverence and wonders at the skill which could come so near perfection working in the dark.

Perfection—that is what the concave speculum has attained of late years. It is possible for a worker of sufficient skill and experience now to set about making a mirror, secure in the knowledge that he can produce a surface in which the most extraordinarily delicate test the human brain has ever devised can detect no flaw. Nay, more, he can produce a mirror whose accuracy is really *beyond* the requirements of telescopic vision. A mirror which has faults quite visible to the expert using Foucault's test will often perform in the telescope just as well as one which has none, because the faults of the faulty one are too small to affect the visual image. The test is, in fact, *unnecessarily* delicate. But then nothing is ever "good enough" so long as it can be improved, and no good speculum maker will let a mirror out of his hands which has a defect which he can see and can remove, however small that defect.

The earnest and industrious speculum worker never really knows to what his efforts may lead him. In most trades the amateur must be content to follow humbly, and at a distance, the steps of the trained professional man. In telescope-making, and especially in the making of the essential parts of the reflector, it is the other way about. The amateur has shown the way to the professional, and forced the pace for him, ever since Herschel's time. Herschel himself was an amateur, so was Lord Rosse, so was With, so were Draper, Common, Calver, Wassell, and Alvan Clark. That many of these *became* professionals only emphasizes the fact that they began work as amateurs and ended by beating the professionals at their own trade. That they did so is largely due to their recognition of the principle expressed in the phrase I have just now used. "Nothing is 'good enough' so long as it can be improved."

The chapters which follow are dedicated to the amateur telescope makers of the world in the hope that some at least of them may be thereby helped on the road which led Herschel, With, Calver, and Clark from humble amateurism to the headship of the world's professional makers. The writer's first telescope was constructed when he was aged ten years, and consisted of a spectacle lens, a sixpenny microscope, and a pasteboard tube, with which humble instrument, innocent of achromatism, he first viewed Jupiter's satellites, the phases of Venus, and the lunar mountains. This was the beginning of the ladder which has already reached more than 140 mirrors of apertures from 6 to 12 inches, and object-glasses of 4, 4½, 5, and 5¼-inch aperture.

Literature

The beginner who seeks for literature to direct his efforts will meet with the difficulty that most of the works on the subject of speculum making are

out of print, or buried in back numbers of magazines, especially those of th *English Mechanic.* Draper's papers are only to be got at in the records of th Smithsonian Institute. The very excellent articles of Francis may possibly b obtainable in a public library in Vol. VII of *Amateur Work.* Wassell wrote i the *English Mechanic,* 1881-8. Browning's "Plea for Reflectors" and Horne an Thornthwaite's "Hints on Reflectors" are both out of print, as is also a usefu little book by W. Banks, F. R. A. S. The only thing of the kind still in prin is a helpful chapter on the subject in Hasluck's "Glass Working by Heat an Abrasion," published at 1s. 6d. by Crosby Lockwood & Co.

Even if all these were obtainable they have one defect in common. The are more or less out of date. The most recent of them represents the state o progress in the art of mirror making existing in 1890-95 or thereabouts. An if nothing else had happened since then, the invention of carborundum i 1898 was sufficient to revolutionize the whole process of grinding, and t place emery out of court as an abrasive. This material, a carbide of silicon and manufactured much in the same manner as carbide of calcium, was firs made at the Niagara Falls Electric Works, and began to come into use fo glass working about 1900. In that year the writer obtained a sample in Dublin and since then has used no other grinding material, except for the very las stage of fine grinding. Carborundum cuts about six times as fast as emery and with No. 80 a 6-inch mirror can easily be rough-ground to curve in les than half an hour, and the whole process of grinding can be done in two an a half to three hours.

CHAPTER II.

Tools and Materials

For the amateur, speculum-making has one great advantage; it does not require an extensive or expensive outfit of tools. Indeed the essential ones need not cost more than a very few shillings. Opticians, it is true, use cast-iron or brass tools, carefully made to gauge and ground true, for forming the curves both of lenses and specula. And where a large number of curved surfaces have to be produced, all of the same radius, these are indispensable. But for the purposes of the amateur mirror or object-glass maker glass tools are preferable, and both their cost and the trouble of making them are negligible. Here, then, is a list of the things necessary to be provided before we begin. It is neither long nor costly:—

1. A pair of equal glass disks.—One for the mirror, the other for the tool. The mirror-disk should have a thickness not less than one-eighth of its diameter—perhaps one-sixth is better still. The tool may be of lighter stuff.

2. A barrel—or, better still, two barrels.

3. A pound or two of pitch.—There are three kinds usually on the market—English, Russian or Archangel, and Swedish or Stockholm. Any of these will do, but Swedish is commonly preferred. As now sold, no cleaning or straining is needed. Purchasable of chemists or oil and color shops.

4. Carborundum, No. 80, 220, FFF.—15M., 30M., and 100M. powders are suitable and sufficient. Sold in 1-lb. and 2-lb tins. Buy from the makers, on no account from the "local shop," or grades may be found disastrously mixed.

5. Jeweler's rouge.—One pound will polish quite a number of mirrors.

The above are indispensable. To these may be added a list of articles not indispensable, but very desirable:—

a. A lathe.—The possessor of a lathe can turn up the blocks and handles which he requires for mounting and holding disks during working, and can do a lot of neat jobs when he comes to mount his mirror and flat. To *make* a flat a lathe is indispensable.

It is very desirable that the grinding and polishing should be done in different rooms. If the worker is lucky enough, or rich enough, to possess the house-room for this, the polishing-room should be provided with its own barrel, and nothing contaminated with carborundum should on any account be allowed to enter it.

b. An oil-stove or gas-ring is almost indispensable for melting pitch, warming glass disks before cementing, etc. (Pitch will not stick to cold glass.) —If the worker resides out of reach of gas and uses an oil-stove, it should be of the central-draught variety, with a circular burner, and its upper works should be stout enough to support a fairly heavy weight.

c. An assortment of enameled iron dishes and basins will be found useful for quite a number of purposes, such as holding water and rouge, and covering tools and mirrors to keep off dust during the intervals of working. Porcelain or earthenware ones are objectionable, owing to the danger of damaging a mirror by an accidental blow against them.

If the worker possesses a lathe, his first job will be to turn up handles and supports for tools and mirrors out of hard wood (oak, box, or mahogany for choice). The usual way of mounting the glass tool is to cement it to a disk of wood an inch or two larger in diameter than the glass. The disk has a wide bevel, and is gripped by three large countersunk screws, the heads of which hold the bevel, as shown in Figure 1, left.

A preferable plan, however, is to have a thick wooden disk, considerably smaller than the glass, screwed securely and concentrically to a stout sheet-iron disk somewhat larger than the glass. The edge of this is gripped by three screws, with a small washer on the head of each. The glass tool cemented to the wood forms a sort of mushroom top. The advantage of this is that it enables us to keep the whole arrangement clean.

Get a sheet of thin zinc, and cut a circular hole in it the size of the wooden disk. Then cut it across, dividing the hole in two. This is placed under the tool, while grinding, with the two semicircular openings closely embracing the wood disk and catches the mud and water which drips from the tool. It is removed and washed as often as may be required, and saves a lot of mess and much risk of scratches in the fine-grinding. (Figure 1, right.)

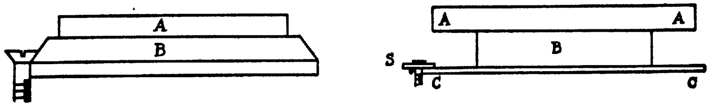


FIGURE 1

TWO WAYS OF ATTACHING THE TOOL TO THE WORK-STAND

Left: A is the tool; B is the beveled disk of wood. Three wood screws hold it in place. Right: AA is the tool; B is a thick, wooden disk; C is a disk of sheet iron; S is one of three screws, with washers. Drip from the edge of A may be caught by sheets of thin tin, cut to fit close to B.

It is well to have a piece of soft deal plank, nicely planed up, and cut to fit on the top of the barrel, to which it is secured with screws. To this the various disks carrying tools are screwed, and when frequent screwing and unscrewing has damaged the wood beyond repair it can be easily replaced. Another disk, smaller than the glasses, must also be turned up. It should be about 3 inches diameter, and is for the handle to hold the mirror. A socket is turned in the center of it, and a cylindrical piece fitted and glued or pinned in place. Now attach the handle to the mirror and cement the tool to its wooden disk, and screw the latter to the barrel top, and we are ready to begin.

ROUGH GRINDING

The next stage is roughing out the curve. The tool is warmed, slightly smeared with spirits of turpentine, melted pitch is poured on the wooden beveled disk, and the smeared side of the glass pressed down on it, squeezing out the excess all round. When cold, the disk is attached to the barrel top. We next warm the back of the mirror, smear a little turps in the center, pour sufficient melted pitch on, and press the handle firmly on. When cemented on it looks like Figure 2, center.

Ordinarily 8 oz. cocoa tins are convenient for melting pitch in. Of this more later on, when we come to polishing. We place a basin of water and a handful of absorbent cotton handy on the work bench and a tin of No. 80 carborundum, strew a little carbo. on the top of the tool, dip the face of the mirror in the water and place it on the tool.

We must now make acquaintance with the mirror maker's "three motions." In order that the desired curve may be produced, the upper disk must (1) travel to and fro across the lower, (2) rotate about its own center, and (3) the worker must walk slowly round the barrel. It is obvious that these three motions could easily be produced by machinery, and for grinding such a machine would work admirably. But it would fail in polishing and figuring. The labor of grinding a mirror of moderate size is not great, and

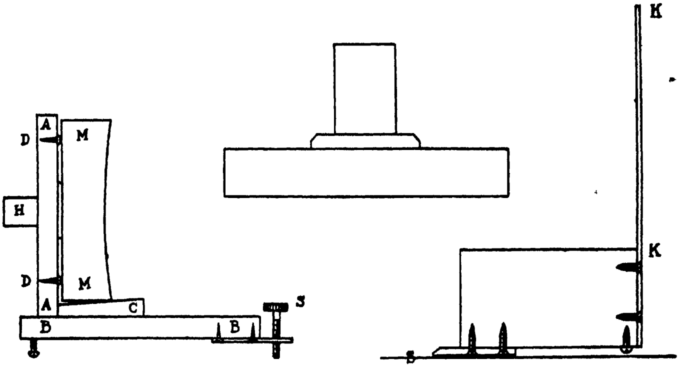


FIGURE 2

THREE NECESSARY ACCESSORIES

Left: The adjustable easel for carrying mirror when testing. Center: the glass disk with wooden handle attached, ready for work. Right: the knife-edge on the block—ED.

hand work is all that we shall need. Motion (1) is known as the "stroke," and by lengthening or shortening it we can produce most useful modifications of the curve. In roughing out, a long stroke is useful—*i. e.*, one as long as possible when the center of the mirror reaches the edge of the tool at the end of each traverse. It produces an irregular curve, of greater depth in the center; but at present this does not matter, as we are more concerned about excavating a hollow as quickly as possible than about its shape. The shape will quickly come right when we begin fine-grinding and shorten the stroke. An elliptical stroke, or "side" stroke, is useful for some purposes, but it slows the cutting.

After working for a few minutes the charge of carbo. begins to get dry; so we lift the mirror and add a few drops of water, and so go on till the

feel of the grinding tells that the abrasive is ceasing to cut. We then lift off the mirror and renew the charge. The older authorities recommended washing the tool and mirror to remove the mud which has accumulated. But this is not necessary at the present stage, and wastes time and labor.

When it is deemed advisable to try how deep the curve is, then we must wash the mirror free from all traces of abrasive, using for this purpose the cotton before mentioned. Absorbent cotton is used instead of the sponge once recommended, because when each stage of grinding is completed the cotton can be thrown away and a fresh, clean bunch taken for the next stage, thus avoiding all possibility of carrying over grit from one operation to another.

To test the curve, the mirror is stood on its edge on a table or shelf, with its surface well swilled with water to make it reflective. The worker stands before it, with his eye on a level with its center, and holding in one hand a candle or small lamp level with his eye. He moves the light to and fro at right angles to the axis of the mirror. If the eye is nearer the mirror than its center of curvature, the reflection will move the same way as the light. If further off than the center, the reflection will move the opposite way. In this way, even with a rough ground surface, the radius of curve can be ascertained within a few inches. The further the fine-grinding proceeds the more accurate this test becomes.

It is not usually necessary to be particular to a few inches about the focal length of a mirror. But sometimes it is required to work as close as possible to a given focus. In such a case the rough-grinding should stop when the radius of curve is still about 8 inches to 1 foot longer than is required, leaving this overplus to be brought down in the next stage. Being more finely ground, the wet surface is then capable of producing a fairly definite image of a light, and we can supplement the method above given of testing the curve as follows: Taking the testing lamp to be described in the chapter on Foucault's test, we substitute for the brass tube carrying the pinholes a tube of perforated zinc. For the knife-edge we substitute a vertical piece of ground glass, and mount this and the lamp abreast on one base. By placing these in the center of curvature of the mirror, we get an image of the perforated zinc thrown on the ground glass. When it is focused as sharply as possible, the distance from mirror to ground glass is the radius of the mirror's curve. A long lath marked in feet and inches is useful for measuring.

It is well to remember that the radius of curve usually shortens about ½ inch in the process of polishing, and this should be allowed for if an exact focus is to be worked to. With care, it is possible to get within ¼ inch of a given focus.

Having roughed out the curve to within a little of the required depth, the next step is to cleanse away most thoroughly all traces of the coarse abrasive. The mirror is well sluiced with water, the tool and its block are detached from the barrel and sluiced under the tap, and crevices scrubbed out with a brush (an old tooth brush is excellent), and the top of the barrel is also well washed with plenty of water.

Now we replace the tool in position, throw out the water in the basin and the old cotton, get a fresh handful and refill the basin with clean water. We

now proceed, using 220 carbo. If the curve is very near the required depth, we shorten the stroke to one-third diameter; but if we are still several inches off the required focus it must be kept long for the present.

If the curve requires no further deepening, six "wets" of 220 carbo. will suffice for this stage. (Each time a charge of carbo. is ground down and a fresh lot applied with water is called a "wet.") Five minutes is an average time for a wet; so each grade of fine-grinding will last roughly half an hour.

We may here add that if a very long stroke has been used in roughing the first effect of changing to short stroke may be to lengthen the radius of curve a couple of inches. It will, however, shorten again, though more slowly, and the effect of the short stroke will be to bring the curve of the mirror approximately to a part of a sphere which is what we want at present. We must persevere with 220 carbo. till the desired radius is quite reached, for the effect of subsequent grades in deepening the curve will be almost nil.

When at length ready to proceed, the washing-up process is carefully repeated, and we change to F F F. Six wets each of this, of 15M., 30M., and 100M., are given, washing up with care after each grade of powder. There is no need to elutriate carborundum, as was formerly done with emery, to obtain the finest grades of all. No finer can be produced than the 100M. * supplied by the makers. Indeed, it may be doubted whether this gives any finer surface than 30M. or 60M. Polishing may be commenced on a surface fined with any of these three.

But we may with advantage use a sixty-minute settling from finest washed flour emery to finish with. A pound of this emery is placed in a large glass jar, the jar is filled with water and well stirred, and then let stand for an hour, after which the liquid is drawn off with a siphon of rubber tube into another jar; care being taken not to disturb the emery at the bottom. The siphoned liquid is let stand till it deposits all the solid matter suspended in it, and this sediment is used to give the final fining to our mirror.

Great care is necessary in this final stage, and also with 60M. carbo. The quantity of abrasive between the close-fitting glass surfaces is so small that they sometimes seize each other and cling so fast together that it is difficult to separate them without a serious scratch. If the disks begin to cling, they should be slid apart at once, lest worse happen.

When the mirror is properly fine-ground it will be possible to read large print through it at some inches distance, or to obtain sharp vision of the sashes of a window at several feet. But the beginner should beware of accepting this as an infallible test of fitness for polishing, as it may consist with the presence of large pits and scratches surviving from the coarser abrasive. The best safeguard against these is to be thorough in the earlier stages of the fining.

The six wets of each grade above described will be found sufficient, if care is taken to grind each down completely. Pressure on the glass is a help to the thoroughness of the grinding, and can have no ill-effect provided the thickness of the mirror is not less than the 1/6 diameter before prescribed.

* This size is no longer manufactured in the United States.—Ed.

Some workers wash the surface of both mirror and tool with the cotton after each wet, but this is not necessary, though perhaps advisable in the 80M. and 60M. stages.

The writer has always made a practice of mixing the finer carbo. grades (15M. to 60M.) with alcohol, and keeping them in corked bottles. The bottle is shaken and a few drops poured out on the tool for each wet, a few drops of water being added. These powders are so clinging that it is difficult to distribute them over the tool dry, and they do not readily mix with water. Moreover, a certain gradation of fineness can be obtained by shaking the bottle vigorously for the first wet, less vigorously for the second, and so on, and very slightly for the last.

Another way of obtaining a final fine-grinding is by making a pitch-tool out of hard pitch. After 60M. is finished with, we carefully wash all up, and replace the tool on the barrel. Dry the surface with a cloth, and smear a little spirit of turpentine over it with the finger tips. Now melt some hard pitch in a tin over the oil-stove. It must be quite thoroughly melted. When completely liquefied, smear the face of the mirror thoroughly with a lather of soap and water, pour the melted pitch all over the tool, take mirror at once and press it down on the soft pitch, moving and twisting it about till the pitch is judged hard enough to retain its shape of itself. Now slide the mirror off, and you have a pitch surface of the same curve as the mirror itself. Let this cool completely, and then apply a thin layer of the 60M. carbo., mixed with alcohol, all over it. Work the mirror on this in short strokes for from ten to twenty minutes, and you get a semi-polished surface, which, if thoroughly done will polish on the rouge tool in about three hours' work instead of the usual six. This method of doing the last stage of fining has the merit of being perfectly safe, both from seizing and scratches.

It is in the last stages of fine grinding that scratches usually originate. A scratch during polishing is rare, and can only result from carelessness, such as approaching the polishing tool with garments or person contaminated with grit, leaving the tool exposed to dust, "spring cleaning" the room when polishing is in progress, etc. (N.B.—The polishing room should *never* be swept, and no feminine hand should ever be allowed, on any pretext whatever, to "tidy" it. Total destruction of a polished surface may be the result of neglect of this rule. "Let sleeping dust lie" should ever be the mirror maker's maxim. It will do less harm on the floor than on his tools or on optical surfaces. A lock on the door and the key in his pocket is the best safeguard.) But all endeavors should be directed to securing immunity from scratches in the fine grinding. Extra care in the washing of tool and barrel and mirror, the provision of a separate basin for the final operations, and covering the work bench with sheets of clean paper will usually secure a clean surface on which to begin the polishing. Very slight scratches need not be regarded, as they will polish out. But even serious ones will often be invisible on the fine ground surface, to start into conspicuous and ugly visibility when polishing begins.

Many workers recommend the use of a pocket lens to examine the surface after each stage of the grinding, in order to ascertain whether all marks left by previous grades have been ground out. The experience of the writer is not

favorable to this as a test. Even the microscope is not always able to tell whether a surface is well or ill prepared before polishing has been begun. The large deep pits and scratches are so disguised by the presence of the mass of small ones that the most experienced eye may fail to detect their presence. It is only after about half an hour's polishing that they start into disastrous prominence. The only real safeguard is to be very thorough with the last, or last two, stages of the fine grinding. Carborundum cuts so fast that 30M. or 60M. will quickly remove even quite deep pits and scratches, and if any doubt remains as to the existence of these, a double dose of 60M. will usually make sure of them. A plan which the writer has sometimes practised is to make a scratch with a diamond somewhere near the middle of the tool, deep enough to be quite certainly deeper than any possible abrasive pit. The edge of the mirror and middle of the tool are the parts which grind most slowly. Therefore, when this scratch grinds out, it may be confidently assumed that all lesser pits are gone.

For the reason just mentioned, that the edge of the mirror gets the least grinding, it is a very good plan to do the last stages of the fine grinding with the mirror face up, reversing the relative positions of mirror and tool. The "mushroom" form of support already described (Figure 1, right) will facilitate this change. In this way that part of the mirror which polishes most slowly (viz., the edge) will get the most fine grinding, and the benefit will quickly become manifest when polishing begins.

CHAPTER III.

Testing; Foucault's Shadow Test

As soon as we begin to polish we immediately require some means of ascertaining what is happening on the concave surface of the mirror, though this knowledge is not of the greatest importance until later on, when we begin the most difficult process of all, viz., the figuring. We might, indeed, go ahead with the polishing, confident that no irremediable error would develop in the curve, so long as the tool was made and used as we shall describe by and by.

Once upon a time it was believed that if a figure of a mirror once became hyperbolic it could not be remedied, and all sorts of devices to avoid the "fatal hyperbola" were resorted to. As a matter of fact, a hyperbolic mirror, though less easy to remedy than some other faulty curves, presents no difficulty to a moderately expert hand, and we could, if we desired, polish away merrily till all marks of abrasion had disappeared, without any testing at all, careless which of the list of possible regular curves turned up at the end of the process.

There are only two limits to this possibility: (a) the limit of human endurance, which prescribes that half an hour's polishing at one spell is enough for the worker's patience; and (b) the limit of endurance of the pitch tool, which begins to soften, from the heat produced in polishing, if one goes on much longer without letting the tool cool down. To this we may add human curiosity, which naturally desires to see how the figure is shaping.

Up to the time of With, speculum makers had to work in the dark, except for tests upon stars, for which one had to wait till the sky chose to clear, and also to dismount the mirror from its handle and mount it in a telescope tube. Naturally, mirror making under these circumstances was a slow and uncertain process. It is owing to the genius of the great Frenchman Foucault that we now have a simple and easy method by which the figure of a mirror is made actually visible to the eye, and so delicately visible that the expansion due to the heat communicated to the glass by the touch of a finger can be clearly seen.

Foucault's method consists essentially in the provision of an artificial star, in the form of an illuminated pinhole. This, of course, cannot be placed at a great distance, so that the light from it will be sensibly parallel, like that of the real stars. It is therefore placed at the center of curvature, and although the resulting appearances differ from those seen when parallel light is converged by a mirror to its principal focus, the two sets of phenomena can be connected by a simple formula.

If the pinhole be placed at the center of curvature of a spherical mirror, it follows from optical laws that all light from the pinhole falling on the mirror will be reflected back exactly to the pinhole again, and will form an image of the pinhole, the same size as the pinhole, on the pinhole. In this position it could not be examined. We therefore slide the lamp a few inches to the left, causing the image to move the same distance to the right, where it can either be examined by an eyepiece or received direct into the eye. Both methods are useful. If the image be allowed to enter the eye, the mirror is seen full of light, like a full moon. Now comes in the second part of Foucault's ingenious plan.

A vertical knife-edge is mounted so that it can be made to slide laterally across the path of the pencil of light, close to the point where it focuses just before entering the eye. When this is done the eye sees the shadow of the knife-edge cross the mirror. Hence the name "shadow test." But the manner of its crossing differs according to the position of the knife-edge with respect to the focus. If it cuts the beam within (nearer the mirror than) the focus a vertical shadow crosses the bright face of the mirror the same way that the knife-edge moved. If it is *outside* the focus, the shadow crosses the opposite way. If it be exactly *at* the focus, the surface of the mirror darkens all over evenly, and looks flat, no moving shadow being seen either way. These are the appearances characteristic of a sphere.

But if the mirror is not spherical, but has some parts of a greater and some of a lesser radius, however small the difference, what will happen? Obviously we shall see the shadow broken up into parts crossing the mirror opposite ways, if the knife-edge is so placed as to be within the focus of some parts and outside that of others—and that however minute the difference may be.

In practice the mirror is mounted on a kind of easel having one screw-foot in front, as a fine-adjustment for raising and lowering (Fig. 2, left). The lamp should be as small as possible, and it is convenient if it can be made to sit in one of the rings of a retort stand, so that it can easily be clamped at any height. A brass tube, with two or three pinholes of different sizes, drops over the chimney. The knife-edge is a vertical strip of steel with a sharp edge, mounted in a wooden block weighted for steadiness and having its forward edge provided with a smooth metal straight-edge (Fig. 2, right). The object of this will be seen later on.

The whole apparatus, with its table, should rest on a stone, tiled, or concrete floor—not boarded. If this is not attainable, then let the mirror easel rest on a bracket bolted to the wall, and the table carrying the lamp be of the stoutest make, and stand on a hearthstone or some similar spot.

The quantities which the apparatus is designated to measure being of the order of millionths of an inch, no movement of the apparatus itself is tolerable.

A convenient form of support for the lamp and knife-edge is a very stout tripod table, with a small top made of soft pine board, planed nicely smooth. Its height should be such that a man kneeling at it can easily rest his elbows on it. It is advisable for the worker to make his own.

We have already seen what are the appearances presented by a spherical mirror when put to the question by the pinhole and knife-edge. But we shall rarely see a truly spherical one. Nearly always we shall have curves with a radius differing more or less in different parts. They will be either (1) radius longer in center than at edge (oblate spheroid), (2) radius very slightly shorter in center (ellipse or prolate spheroid), (3) radius a little shorter still in center (paraboloid) or (4) radius very much shorter in center (hyperboloid). Of these, (1) and (2), as well as the sphere, are under-corrected; (4) is over-corrected, and (3), the paraboloid, is truly corrected, and this is the curve which we desire to produce.

There are, of course, besides these an infinite variety of irregular figures, which may be combinations of any two or more of the above, or figures not

symmetrical, such as astigmatic curves produced by "flexure" (strain, or bending of the glass). The last is not likely to be met with if good glass of proper thickness is used and the directions already given as to mounting and holding it are followed. But if a disk of glass be cemented to a stout wooden block covering the whole of its back, as we have known some beginners do, it is pretty certain to be flexured; and a flexured mirror is rarely curable. The most usual irregularities are hills or hollows in the center, rings, and "turned-down edge." For the present it will only be necessary to be able to recognize the appearances presented by the principal types of regular figure, viz., oblate spheroid, sphere, paraboloid, and hyperboloid.

We have put the lamp on the left and knife-edge on the right, reversing the order of Francis, Wassell, and Draper, as a matter of convenience. It is most important that the knife-edge should be next the observer's right hand, as very delicate movements of it have to be controlled. The lamp is never moved when testing. A little practice and thought on the cause of these phenomena will enable the beginner to distinguish a hill on his mirror from a hollow, even if the nature of the irregularity is not obvious at first sight.

The lamp used in these tests may be any small-flame one. A small Argand burner, with a narrow chimney, is perhaps the best. The smaller the source of light the nearer the knife-edge can approach the pinhole, and the less will be the *ecart* needed of pinhole and knife-edge from the actual optical axis of the mirror. They should not be too far from the axis, or distortion of the shadows will result; and, contrary to the opinion of many workers, the pinholes should not be too small. It is convenient to have two—one of liberal size, pierced with an ordinary sewing-needle, for rough-testing, and a small one, made with the point of a very fine needle, for fine work, eyepiece testing, and testing a mirror after silvering. We have known grotesque errors result from using too fine a hole. Indeed, on one occasion an absolutely perfect mirror was sent to the writer to correct for a "turned-down edge," which was entirely non-existent except in the owner's testing apparatus. He used an acetylene flame and an excessively tiny pinhole, with the result that he saw a series of diffraction bands inside the margin of his mirror, and took them for a turned-down edge. An eye-piece test will instantly detect a turned-down edge if any be present, even if too slight to notice with the knife-edge. But of this later.

It is convenient to cut two openings in our brass tube, opposite each other, cover the whole with a sliding collar of very thin sheet zinc, and pierce the holes in this, one in each opening. Lest the arrangement should collapse if the chimney should over-heat, it is perhaps well to avoid the use of solder, and to secure the zinc collar to the brass by means of a spring clip. A piece cut from a clock spring, of the requisite curve to encircle the tube, answers well.

Another way is to file the brass tube nearly through, and then pierce the thin remaining metal with a needle. But there is considerable advantage in being able to adjust the pinholes higher or lower in the tube, which, of course, is impossible if they are pierced in the metal of the tube itself.

CHAPTER IV.

Polishing

Having provided ourselves with a Foucault's testing apparatus, we may now proceed to polish. The glass tool on which the mirror was ground is, with its wooden block, removed from the grinding barrel, thoroughly scrubbed and sluiced with water, to clean away all trace of abrasive, and transferred to the polishing barrel (and polishing room if we have one). Dry its fine-ground surface, and smear a little turps over it. Meanwhile a tin of pitch will be melting over the oil-stove. This should be carefully watched, and stirred frequently with a short stick.

It is a very great improvement to add to the pitch about 5 to 10 per cent. of beeswax. The effect of this will be appreciated when we come to cutting out the facets on the tool. Pure pitch is abominably sticky, and also is liable to fly into tiny chips when cut. These adhere to the skin, hair, and clothing, and are more than likely to conduce to profanity, being very difficult to get rid of. The wax-pitch mixture does not chip, and its stickiness is so much reduced that it can be molded with the fingers when soft without adhering. Still more important is what may be called its "flexibility," using the word in the motor-engineer's sense. Pure pitch, to work well, requires to be very close to the ideal degree of hardness. If it is too soft it very rapidly produces a deep hyperbola, and also a "turned edge," the dread of all the old mirror makers. If too hard it scratches. But the wax-pitch mixture will work well, within much wider limits of hardness, and seldom produces a turned edge.

It should be just possible to mark it with the thumb-nail when cold.

Watch that the pitch does not boil, and if it shows signs of doing so, lower the lamp. Prolonged heating hardens it. To soften, add carefully a little spirits of turpentine. (Do not spill any over the lamp, or there may be an explosion.) Not more than a teaspoonful should be added at once, as its effect is quite disproportionate to its quantity.

While the pitch is melting we get the mirror ready by standing it face up and painting it all over with a thin paste of rouge and water. We will require two or three glass jars (such as 1-lb jam jars) and a plate of glass to cover each to exclude dust, a camel's-hair brush, large and flat, and a knife, or, better still, an old razor. We also need a stamping tool. To make this, take a piece of nice cleanly-planed wood with straight faces about 9 in. x 1¼ in. x 2 in. Cut two pieces of thin hoop-iron 9 in. long, and file one edge of each to a wedge-shape. Clean both pieces up well with a file, drill three or four holes in each, and screw them to the sides of the piece of wood, so that their sharpened edges are parallel and 1¼ in. apart. This is our stamp for marking out the facets of the tool.

Mix in one of the jam-jars a tablespoonful of rouge with water to a thin cream, and paint some of it over the face of the mirror with the camel's-hair brush. When the pitch is quite liquid all through grasp the tin with a cloth, and pour it out rapidly on the tool, beginning at the edge, going inwards with

a spiral motion and ending at the center, where a considerable excess may be poured.

Lay the tin aside and at once take the mirror and press it face down on the semi-fluid mass, twisting it round and moving it to and fro for several minutes, or till the pitch is cool enough to retain its shape. It will overflow all around the tool. Let it stay there. It will do no harm and will safely imprison any bits of loose grit that may be present.

The layer of pitch on the face of the tool should be about $\frac{1}{8}$ in. deep, not more. When it is judged time, slide the mirror off, lay it aside, and take your stamp and press it lightly on the still soft tool. It leaves the impression of its two parallel edges. Lift it and place the second edge in the furrow of the first and press again. When you have gone across from side to side repeat the operation at right angles. The tool is now covered with systems of parallel lines, the two sets being at right angles to each other and dividing the surface into squares of $1\frac{1}{4}$ inch side.

Now we take the old razor and proceed to cut out V-shaped channels about $\frac{1}{8}$ in. wide along these lines. Cutting down to the glass, the strips cut out can be lifted clean out, leaving clear V-shaped furrows. We could not do this with pure pitch. We also get a criterion of the hardness If the strips cut and lift out without either elongating or breaking up into bits, the hardness is just about right. A strip when cold should bend just a little before breaking. If it will bend nearly double without breaking it is too soft.

But there is one point about the facets which we have not mentioned, and it is an important one. The center of the tool must not be near the middle of a facet, nor must it be in a channel. It should be *in the corner* of a facet. If not, the mirror will polish in rings. It is a good plan to mark the center with a pair of compasses before using the stamp and then to stamp the lines embracing the center first.

The older workers, and especially Wassell, were very particular about the *shape* of the V-grooves, that the slope of the sides should be exactly 45 degrees. This, like too many of the older refinements, is pure bosh. It does not matter in the very least what the shape of the grooves is, provided they are hollow enough to give clear air channels under the face of the mirror. Nor does it matter what the shape of the facets is either. We only make them *square* because that is easiest. The $1\frac{1}{4}$ in. squares will do for all sizes of mirror from 6 in. to 10 in. Above 10 in. we may double the size and make them $2\frac{1}{2}$ in. Below 6 in. they may be dispensed with altogether.

The cutting of the facets will somewhat disturb the curve. As soon as it is finished, therefore, while the pitch is still a little soft, we must paint the tool over with the rouge and water, and place the mirror on and work it a bit, say for five to ten minutes, meanwhile observing through the glass what is happening. Probably at first the central facets will not be entirely in contact with the glass. We must work, if necessary, with pressure, till all air bubbles disappear and all facets are in contact. And here we find the advantage of having the back of the mirror transparent. We will find it again when silvering. Many makers grind the back; a foolish and a totally unnecessary proceeding. The only possible object of it is to prevent light which passes through

the silver film from being reflected from the back to illuminate the field of view. I have elsewhere shown that the maximum possible amount of light so returned could not exceed that of a 12th mag. star distributed over the entire field. So do not grind the back, and both figuring and silvering will benefit.

Now, having the tool in order, we proceed to polish. The motions are just the same as in fine-grinding. But now we must time ourselves. It is by time that we judge how much polishing the mirror has had. So a clock forms part of the furniture of the polishing-room. Another useful article is a thermometer, which should be hung not against the wall, but freely out in the room. A rise or fall of even 5 degrees in temperature will greatly affect the behavior of the tool. A rise softens the pitch and a fall hardens it; consequently, a change of temperature may quite alter the character and effect of our tool. For this reason, as well as for another, to be explained later on, a light building of wood or iron is totally unsuited for a polishing place. The best place of all is a cellar or basement below ground, where the temperature will remain reasonably constant. In any case it must be a building with substantial stone walls. And the sun should not be allowed to shine in if it has a large window. Especially it must not on any account shine on the tool, or we may have to remake the latter.

Having fully taken in these *caveats*, we may begin our first spell of polishing and go on for half an hour by the clock, using short strokes, and only stopping occasionally to renew the rouge and water. A dish of clean water, with a short stick having a large handful of absorbent cotton tied round one end, in it, will be found useful on the work-bench. This is to wash the rouge off the mirror when we stop to test, and keep our hands out of the mess. We also will need a few pieces of old linen, quite clean, for wiping the optical surface dry.

It is well to keep a written record of the spells of polishing and of the figure found at the end of each. At the end of the first spell the mirror should be semi-polished all over, rather more in the center. We may possibly find a very eccentric figure at this stage; perhaps a very exaggerated hyperbola. But do not mind. Go on, and it will come to reason later on. And if it does not, but gets worse, which is not likely, remember that any figure made by polishing can be unmade by polishing. It can never be necessary to regrind, no matter how eccentric the figure.

But it is more than likely that it will be found to be somewhere near a sphere. In any case go on. We are only polishing, not figuring, and have at least three hours' polishing before us before the figure matters at all.

The mirror should work easily, and smoothly on the tool. If it does not, but sticks and clings, the curves cannot be truly coincident. In this case it is useful to leave the mirror on the tool for several hours, with plenty of rouge and water between, to prevent sticking together, and three blocks of wood round to prevent sliding off.

After the first half-hour's polishing we may use the microscope to ascertain the prospects of quick polishing. A 1-in. objective is suitable. With this all pits and scratches are visible, and we can see if any deeper than the average are present. If none but the finest are visible we may expect to polish in

about three hours, or even less. The outer ½-in. of the mirror is all that need be examined, as this zone is always the slowest in polishing.

If the successive stages of fine-grinding have not been done with sufficient thoroughness it will be quite easy with the microscope to identify the pits due to the successive grades of abrasive. Moreover, the appearance of emery pits is quite different from those due to carborundum. The latter are sharp-edged tiny holes, deeper than they are wide; those from emery are much more diffused, and naturally polish out quicker. Hence the advantage of an emery finish to the fine grinding.

We shadow-test, just for curiosity, before going on, for it is little likely that any errors gross enough to require a change of tool will be seen. Then we proceed to another half-hour's spell, and so on till the surface begins to look well polished to the naked eye.

During the preliminary polishing the water in the dish will be getting more and more stained with rouge. When it is no longer able to cleanse the mirror set the dish aside and take a clean one and a fresh lot of water. After the first dish has stood for twenty-four hours its charge of rouge will have settled. Pour off most of the water and with what is left rinse the dish round well, and pour off all but the last few drops into a clean 1-lb. glass jam jar, and put it aside covered with a glass plate. This will give us a reserve of extra-fine rouge for the final stages of figuring. This may be repeated as often as the water in the dish becomes too deeply stained to cleanse, and the fine rouge settled from the rinsings is most important in obtaining a surface clear of the tiny scratches rouge is apt to make.

Some samples of rouge are very scratchy, and cannot be used at all without treatment. They may be stirred up in a jar of water and poured off after ¼ to ½ minute's settling. But a better plan is to make the rouge into a paste with water and then ladle the paste by spoonfuls into a flannel bag. Place this bag when full in a jar of water and knead it well under water. The fine powder comes through the bag and all coarse particles are left inside. It is a messy job, but worth while.

When we can no longer see any defect of polish with the naked eye we once moie inquire of the microscope, and if no abrasive pits can be seen in the marginal zone of the mirror all is well so far as the polishing is concerned.

CHAPTER V.

Figuring

We now come to the *crux* of the whole process. Grinding and polishing are purely mechanical processes, which any handy man should be capable of learning in a few lessons. But the man who can produce a perfectly true paraboloidal curve right up to the edge of a mirror is not a mechanic, but an artist; and the artist is born, not made. Volumes might be written on the art of figuring, and the reader of them would be no nearer being able to produce a true curve after reading them than before, if the talent were not born in him.

Much depends on the figure which we find present at the completion of polishing. If it is a sphere, or an oblate spheroid, of a moderate amount of oblateness, and with no complications, such as turned-down edge, we may go ahead with the tool we have been using, taking to the fine rouge collected as described already. We have merely to deepen the curve very slightly towards the center. There are several ways of doing this. We may classify them:—

1. Parabolizing by long stroke.
2. Parabolizing by graduating facets.
3. The small polisher system.
4. Parabolizing by overhang.

The first two are old methods, and are described in all articles on the subject, from Herschel to Wassell, and later.

(1) Parabolizing by Long Stroke

We have been polishing in short strokes of about one-third diameter, and straight (center over center). If we now increase the *length* of stroke to one-half, two-thirds, or whole diameter, we shall get a more or less rapid hollowing of the central region of the mirror.

If there were no complications to this method, parabolizing would be easy; but, unfortunately, long stroke very often means producing a turned edge. It must, therefore, be used sparingly, and with discrimination. Supposing, for example, that the figure we have to parabolize is a sphere with a turned-*up* edge, we may use long strokes for a while, being careful not to overdo it. Dealing with an oblate spheroid in the same condition, we might use it a bit more freely. Resort must be had to Foucault's test at frequent intervals. But where there is a question of a turned-*down* edge we require a control on Foucault's test.

Very few mirror-workers are capable of detecting a turned edge by Foucault's test alone unless the turn-over is very gross. But an *eyepiece* test will decide the matter at once. For this we require an eyepiece of about one inch equivalent focus and a fitment to hold it which will stand in another ring of the retort-stand which carries our pinhole-lamp. To use it we simply remove the knife-edge out of the way, and slide the ring carrying the eyepiece down into its place till we can see in the latter the image of the pinhole. If the figure of the mirror is near a sphere the image will be nicely sharp. Now slide the whole stand, lamp, eyepiece and all, alternately nearer to, and further from,

the mirror, so that we get the image out of focus. If the image, when some distance inside focus, is a circular disk, with a clean, well-defined edge, the curve of the mirror is true to the very edge. But if the disk has a hairy, fuzzy, and ill-defined outline, the edge of the mirror has a flatter curve than the rest; in fact, it is "turned down." This test is infallible and extremely delicate for this one defect.

The expanded disk, outside focus, is *always* sharp in outline. Even when the mirror has a turned-up edge the appearance is not reversed, as we might

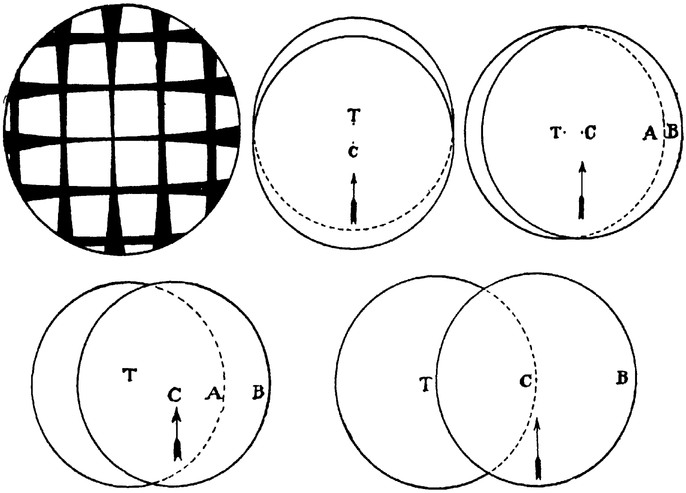


FIGURE 3

Upper left: Tool graduated for parabolizing. In each of the four other diagrams the complete circle represents the mirror and the arrow the direction in which its center, O, is moving to and fro. T is the center of the tool. In the first drawing, C passes over T at each stroke. In the second, third and fourth, C passes at greater and greater distances to the right of T, according to the effect required. In the last drawing the center of the mirror works on the edge of the tool. Not to be recommended unless central hill is to be removed, and then very cautiously.

suppose. In this case the outside-focus disk will have a slightly softer outline than usual, while the inside-focus one will be very sharp. In using this test, however, we must remember that the paraboloid which we are trying to produce is a figure which becomes flatter towards the edge. Therefore, we must not aim at getting the inside-focus disk too sharp. It should be just a little softer in outline than the outside-focus one when the mirror is finished. But a hairy edge to it cannot be tolerated.

The turned-down edge is the mirror maker's *bete noire.* Formerly it was considered impossible to escape it, and older makers used as a matter of

course to grind off the outer half-inch, or advise stopping the mirror down. But we know better now. As the "fatal hyperboloid" is now no longer incurable, neither is the almost equally dreaded turned-down edge.

(2) Parabolizing by Graduating Facets

This is the standard method of bringing an oblate spheroid or a sphere to a paraboloid. It seems obvious that if we reduce the size of the facets of our tool, progressively from center to edge, by widening the channels between them, we shall increase the amount of abrasion in the central parts relative to that near the edge, and thus will obtain the desired result of a deepened curve near the center, without increasing the stroke or imperilling the curve of the edge. The alteration will be made as shown in Figure 3, upper row, left.

This is, perhaps, the easiest method of graduation. It might also be done by leaving the middle facet as it is, trimming off the corners of the three nearest to it, and cutting those next in order down to circles, and yet smaller circles. This will often produce the desired effect, but not always. It is well to use a broad chisel and light wooden mallet for trimming facets and keep a large, soft brush handy for sweeping the tool free of chips. This should be kept in a dust-proof receptacle.

The above two methods of parabolizing are standard methods of all the old masters of the mirror-working art. Those that follow are the result of experiments of the present writer.

(3) The Small Polisher System

It has always been laid down as axiomatic that mirror and tool must be the same diameter; but, like many axioms of the old workers, this principle has no other foundation than their fear of attempting new methods. It is quite easy to both grind and polish on tools considerably smaller than the mirror. And what we have called the "Small Polisher System" is often useful as a remedy for the great enemy, "turned edge." A polisher a little less in diameter than the mirror, of hard pitch, used with short, straight strokes, will often remove a turned edge when everything else has failed. A polisher considerably less than the mirror, even so far as only two-thirds diameter, will rapidly hollow an obstinate oblate spheroid. Naturally, this requires to be used with caution, stopping every few minutes to test, lest a deep hyperbola result.

(4) Parabolizing by Overhang

Cutting and trimming the pitch tool is always more or less objectionable, if for no other reason than that it cannot be undone, once done, without the trouble of destroying the tool and making a fresh one. But without making any alteration in a satisfactory tool it can be made to cut the central region of the mirror faster as follows. Observe the four positions in Figure 3 (the figure at top left being excluded).

The first one shows the ordinary center over center stroke, with which we have been working. When the centers coincide, of mirror and tool, the weight of the mirror is equally supported all over by the tool.

But if instead of letting the center of the mirror pass over the center of the tool at each stroke, we bring the mirror a little to one side, as in the second, so that the crescent AB of the mirror is always off the tool, obviously the region of the mirror between C and A will be supporting the whole weight of the mirror, and will be pressed against the tool more forcibly than the rest of the surface. If, therefore, we polish with the mirror in this position, the mirror, as before, rotating about its center, and the worker walking round the barrel, we will get a greater abrasive effect in that part of the mirror, whose radius is CA.

And if we increase the overhang, as in the lower left, we further narrow the part of the mirror supporting its weight, and further concentrate the abrasion in the central region.

While if we place the mirror as in the last drawing of the group of four, with its center on the circumference of the tool, we get the whole pressure, due to the weight of the mirror, supported on its center alone. To work in this position would rapidly produce a deep hollow just in the center. It is therefore useful for removing a central hill, but it is not to be recommended except in such a case, and then very cautiously.

We have, therefore, in this method of "overhang" (so called because the mirror always overhangs the tool by a certain amount laterally during the entire stroke) a most valuable means of controlling the figure. It is obvious that we can work the overhang method with an elliptical or circular as well as with a straight stroke, and also that we can alternately increase and diminish the amount of overhang as we work. In this way we can distribute the extra abrasion due to overhang almost *ad libitum* over any required area about the center of the mirror, and therefore can probably produce a paraboloidal curve more easily by this method than by any other.

In all these operations it is well to have the back of the mirror protected from the heat of the hands by some non-conducting material. Otherwise a good deal of trouble may result, and the success of figuring may be considerably retarded. A piece of thick pasteboard cut to a circle the size of the mirror, and with the center cut out to admit the handle, will be found useful.

Working Uphill

So far we have been trying to bring the figure of our mirror from sphere to parabola, or from oblate spheroid to parabola, via sphere. Now this is the way that the figure of a mirror, if left to itself during polishing, will travel nine times out of ten. We therefore call it working "downhill."

But, supposing we have, to begin with, a more or less hyperboloidal figure, or that we have, in bringing the figure downhill by any of the above methods, overshot the mark, as very often happens, and obtained a hyperboloid, we will have to find means to make the curve retrace its steps. As this is considerably more difficult (it used to be counted impossible, hence the term "fatal hyperboloid"), we may call it "working uphill."

To begin with, we may lay down the principle that a hard polisher pulls the figure uphill, whereas a soft one lets it downhill. But we may as well say here at once that although various types of pitch polishers are calculated

to produce certain definite effects, the pitch tool is most delightfully inconsequential in its behavior, and one never knows for certain what any given tool will do till it is tried. It is as *varium et mutabile* as any woman, and a speculum maker may fancy that after some years of experience he has fathomed all that pitch can do when it will suddenly surprise him by some totally fresh whim.

However, the first thing to try, for a hyperbola as well as for a turned edge, is a hard tool and short strokes, and three times out of four this will be successful. If, however, it is not, we must try graduating the facets in the opposite way to that shown in Figure 3 (upper left) cutting down the central ones and leaving the marginal ones full size. In extreme cases of a very deep or

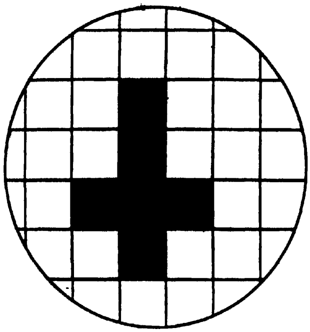


FIGURE 4

Facets shaved from the tool to reduce a hyperbolic figure.

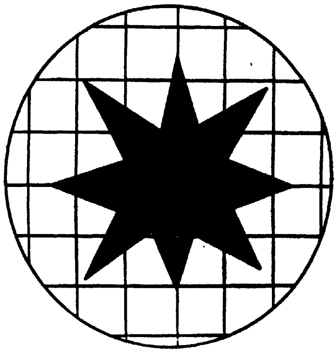


FIGURE 5

Another way to reduce a hyperbolic figure. This is more suitable than Fig. 4 for small sizes.

obstinate hyperbola the whole center of the tool may be removed bodily, leaving only a ring of pitch. This will probably result in an irregular oblate spheroid, whereupon we make a fresh tool, and proceed to work downhill again.

A shape which the writer often finds useful to bring a hyperbola to reason is an ordinary tool having a wide, rectangular strip the breadth of one, or even two, facets, removed right across the center, or having two such strips, one a facet longer than the other, crossing each other, as shown in Figure 4. It must not be supposed, of course, that this arrangement will produce a regular figure. It will probably result in a large hump in the center. When the center is sufficiently raised we can then make an ordinary "downhill" tool, and work towards a paraboloid again as before. If we have got, as sometimes happens, a figure, which is not exactly a hyperbola but has a big hollow in the center, the above tool, carefully used, may, with luck, bring it just right.

It sometimes happens that a ring, either raised or depressed, appears on the mirror. A polisher which rings the mirror probably has its center in the wrong place with respect to the facets. The ringing action may be reduced, or even entirely suppressed, by using an elliptical stroke, or "side," as it is sometimes called. "Side" tends to turn the edge, though not to the same extent as long stroke, and therefore should be used sparingly. A single depressed ring on an otherwise promising figure may be eliminated by cutting out two or three facets along the path of the ring, reducing the abrasion of that particular zone. A raised ring is more difficult to deal with. If not far from the circumference it may be removed by the "overhang" method, working so that the edge of the tool just traverses along the raised zone. It may also be dealt with by very cautious use of a polisher all cut away except a ring of

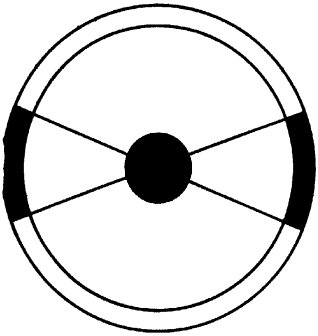


FIGURE 6

A cardboard stop for use in measuring the depth of parabolization. This style is termed Stop I.—ED.

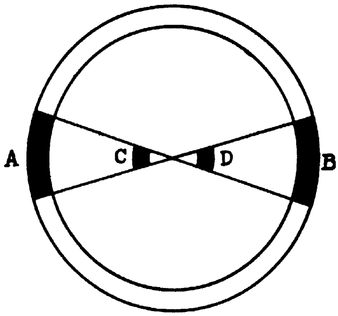


FIGURE 7

Another kind of stop, termed Stop II. The bottom of the stops may be shaped so that they will stand steadily.—ED.

the same size. A very few strokes at a time should be attempted on this, or we may get a depressed ring instead.

Having overcome these difficulties we will suppose we are now approaching the desired paraboloid. There are several difficulties of another kind to be met before we "get there."

If the worker be at all observant he will have noticed before this that the figure seen on testing immediately after removing the mirror from the tool is quite different from what appears some time later, when the mirror is allowed to rest awhile. The cause of this is, briefly, temperature. The friction of mirror on tool produces quite a considerable amount of heat, and we shall find that there is a very definite law connecting the figure of a mirror with its condition of temperature relative to the surrounding atmosphere. Briefly stated, the law is as follows:—

When a mirror is cooling its figure is temporarily pulled "downhill," or

in the direction of the hyperbola. When a mirror is warming its figure is temporarily pulled "uphill," or towards the sphere. (This, by the way, is the real reason why a slight under-correction is always given to specula by the best makers. A mirror, when in use on the heavens, is nearly always cooling slowly, with the atmosphere of a clear night. Consequently if its figure were a full paraboloid it would always, under working conditions, be a little over-corrected. To avoid this it is left a little under-corrected in the workshop.)

The result of this law is that we can never see the real figure of a mirror immediately after taking it off the tool. In fact, if we see a parabolic figure then, and leave it a while to cool, we shall find that it has changed to a sphere, or even an oblate spheroid. To obtain a paraboloid when cool we must have a very pronounced hyperboloid on taking it off the tool. At least half-an-hour must elapse before the true figure can be seen. Ignorance of this has caused endless trouble to beginners; for in order that the figure of a mirror may be all right it must look all wrong when just taken off the tool. Consequently, when approaching completion of our mirror, we have to pass through a period of working for a few minutes, and then waiting half-an-hour to see the result.

CHAPTER VI.

How to Recognize the Paraboloid. Zonal Testing

The "Temperature Effect" is not the only difficulty to be encountered at the critical stage when we are nearly "there," but not quite. The question arises, "How are we to recognise the paraboloidal curve when we get it?" This is a very real difficulty. The only difference visible in testing between a true curve, one a little under, and one a little over-corrected, is a difference of *depth of shading.* We cannot leave this to mere personal judgment. We must have a means of distinguishing accurately. And this is the more necessary as the depth of shade in the parabola *varies enormously with the ratio of focal length to aperture.* The same shadows which would indicate a beautiful parabola in a mirror whose ratio was *f.* 8 (as the photographers conveniently call it) (*i. e.,* whose focal length was eight times its aperture) would mean a deep hyperbola in a mirror of *f.* 9. And when we get much beyond *f.* 10 or *f.* 11 we can *see no parabolic shadows at all.* If shadows can be seen in such a mirror it is hyperbolic. In other words, the difference between a sphere and a paraboloid in such a mirror is too small to be seen. It can, however, be measured.

We have already learned that when testing a spherical mirror, with the knife-edge just cutting the converging beam exactly at the centre of curvature, the mirror is seen to darken evenly all over. In other words, the difference of radius of curve for center and all zones distant from the center is zero. In the paraboloid and hyperboloid the radius of curvature increases outwards from the center. In the oblate spheroid it diminishes outwards.

Therefore, if we place over the mirror a stop which covers all its surface except a small area about the center, and adjust the knife-edge till this area darkens evenly, and then substitute for the first stop another which covers all except a strip of margin, if the mirror be a paraboloid we shall have to move the knife-edge a little way *further from* the mirror to get this marginal strip to darken evenly; and if it be a hyperboloid, a little further still.

And if we know *how much* the knife-edge must be moved back for a paraboloid we shall have an accurate means of recognizing the desired curve when we see it.

Now, the mathematicians have given us this information, and it is enshrined in the simple and easily remembered formula $\frac{r^2}{R}$ where r is the radius of the mirror, or of any zone thereof, which we desire to test, and R is its radius of curvature. For example, if we are testing a $6\frac{1}{4}$ in. mirror of 4 ft. focus (*i. e.,* 8 ft., or 96 in. radius), $\frac{r^2}{R} = \frac{3^2}{96} = \frac{9}{96} = 0.093$ in.

Therefore, if we find that, after adjusting the knife-edge to the radius of the center we have to move it back .093 in. (nearly 1-10 in.) to get the marginal zone to darken evenly, the mirror is a paraboloid, always provided that the mirror, tested without a stop, shows a *regular* curve, *i. e.,* is free from rings, hills, hollows, or turned edge.

Some workers prefer to test a whole series of zones, and tables are given of the values of $\frac{r^2}{R}$ for all diameters of zone and all focal lengths. It is, however, very trying to the eyes to test a long series of zones, and it is not necessary. For the open shadow test tells very clearly and unmistakably if the *general curve is regular.* And then it is only necessary to test the difference between the center and marginal zone, for if this is right and the curve is regular all the other zones *must* be right.

Now we can understand the object of the metal straight-edge attached to the stand of the knife-edge (see Figure 2, right). We pin a white card to the top of the testing table with a couple of thumb-tacks, stand the knife-edge on it, and when we get it adjusted for the center of the mirror, hold it firmly down, and draw a sharp-pointed pencil along the straight-edge.

Now we adjust for the marginal zone, and repeat the process, taking care to keep the block in which the knife-edge stands parallel to the edges of the card.

Now we have a pair of parallel lines on the card, and the distance between them will be $\frac{r^2}{R}$ if *our mirror is parabolic.*

Many and elaborate are the arrangements devised by Wassell and others for making this simple measurement. Micrometer-screw movements in two directions, springs to take up slack, scales, and microscopes to read them. The writer has tried them all, and ended by "chucking" them in favor of the simple method above described. The straight-edge, pencil, parallel lines on the card, and a pocket-lens and scale of 50ths of an inch, to measure the distance apart of the lines, are sufficient. The simpler a method is the better, provided it gives the desired result. And in all this little book the object before the writer has been to reduce everything to the maximum of simplicity consistent with efficiency.

The stops above referred to may conveniently be made of pasteboard. For each size of mirror two circular pieces may be cut, the exact size of the mirror. One has a circular hole cut in the center, a little larger than the minor axis of the flat which is to be used with the mirror, *e. g.,* for a 6¼ in. mirror a hole 1½ in. diameter will be suitable. From opposite sides of the margin two pieces are also cut, as shown in Figure 6. The shaded portions are those cut out. The width of the marginal zone may be ½ in. for mirrors of 4 to 5 ft. focus, but must be wider for ones of longer focus, owing to the greater distance from which it must be read. The other disk may be cut thus (Figure 7). The cross-lines and the inner circle are only for guidance in cutting.

The stops having been prepared, the mirror is placed on the easel, a card is pinned to the top of the testing table, and the knife-edge put in position and adjusted to the proper position for shadow testing. Care should be taken to place the straight-edge parallel to the sides of the card, and the sides of the latter parallel to those of the table.

The stop is now placed on the mirror. (The writer prefers stop I., but II. is the form most frequently used.) Let us suppose we are using No. II. What shall we see? Let us consider first zones A and B. As the knife-edge is

advanced across the beam of light, one of three things will happen. Either zone A darkens while B remains bright, or *vice versa,* or they both darken equally.

The observer must practise his judgment in deciding which of the two is the darker, as in reading a Bunsen's shadow photometer. If both are equally dark, the knife-edge is *at the focus of this zone,* and the pencil may be used to mark the position of the straight-edge.

Now *before moving the knife-edge,* observe the appearance of the zones C and D. If the mirror is parabolic or hyperbolic, the knife-edge when at the focus (center of curvature) of the zone A B will be *outside* the focus of zone C D, because in these curves the center has the shortest radius. Therefore, when A and B are *equally dark,* C will be *darker than D.* The knife-edge must therefore be moved *towards the mirror* a little to make C and D become equally dark. When they are judged equal, the pencil is used again. If the distance between the pencil lines is equal to $\frac{r^2}{R}$ the mirror is exactly corrected.

In practice it is always advisable, for the reason already stated, to leave the correction a little less than $\frac{r^2}{R}$ Thus in a mirror where $\frac{r^2}{R} = 0.10$ in. 0.08 in. would be a good correction. Even 0.06 in. might pass as sufficiently corrected. In any case a number of readings should be taken, and the mean of them all adopted as the true reading.

The chief difficulty the tester will meet with is the difficulty of deciding the exact point where C and D are equally dark. It is far easier to decide between A and B, owing to the more obtuse angle subtended by these at the center of curvature. Therefore, it is well to take a number of readings of C and D, sometimes taking the knife-edge well inside their focus and working outwards, and at other times well outside and working inwards. It is for this reason also that we recommend the stop of the form No. I., as it is somewhat easier to decide when the shadow in the central hole *travels neither way,* but comes on equally all over the hole, than to decide between the relative shades of the two slots C and D. If these slots are too narrow, the eye is very apt to be misled.

In the case of a long focus mirror, decision is naturally very difficult. Take, *e. g.,* a 6 in. of 6 ft. focus. In this case $\frac{r^2}{R} = \frac{7.29}{144} = 0.05$ in. Therefore 0.04 in. will be a good correction. The observer will find that when A and B are equally dark it will be difficult to decide that C and D are not equally dark also. In fact, 0.04 in. is a very usual margin of error between two readings of C and D, so that the real difference between the two pairs of zones is not greater than the possible error of observation.

Everyone who is accustomed to making delicate instrumental measurements knows how difficult it is to obtain a reliable reading under such circumstances. Therefore the mirror maker should beware of extreme focal lengths; *f.* 8 to *f.* 9 is the easiest for purposes of accurate correction. We have never yet seen a mirror of *f.* 10 and upwards, even by well-known makers, that was not over-corrected. Foci of *below f.* 8 are objectionable for another reason, though

when we get to apertures of 15 in. and above, considerations of space, weight of mountings, etc., make it necessary to adopt short foci. The trouble with these is that the wide-angle cone of rays upsets most eye-pieces, unless they are specially calculated for the purpose. Ordinary negative eyepieces give quite an unpleasant amount of false color on mirrors of *f.* 7 and *f.* 6, and really spoil the perfect achromatism of the reflector. Achromatic eyepieces should be used with all mirrors of focus below *f.* 8 if the finest definition is to be obtained.

In conclusion of this part of the subject, let us again repeat the warning given before with respect to temperature. It is absolutely necessary, the *sine qua non* of success, that testing shall be carried out in a place in which equilibrium of temperature can be maintained. The best of all places is a cellar completely underground, and free from draughts. If this is not available, the next best place is a basement room, partly underground. And if it must be above ground, it should be done in a substantial stone building, with as little window space as possible. It is *quite impossible* to get true readings in a living room, or any place artificially heated. It is equally impossible in a lightly-built workshop of timber or galvanized iron. In fact, such a building is hopeless for the mirror maker's work, except for the roughest parts of it.

Polishing, not to mention figuring or testing, is impossible in a place where the temperature may vary 20° or 30°, according as the day is sunny or cloudy. Testing *in the open air* is equally impossible. And this last is tantamount to saying that *testing on a star* is useless, for a star-test is necessarily in the open air. It sounds no doubt plausible to say that as a telescope is made for observing stars, its performance on a star must be the best criterion of its quality. But it is to be noted that this plea is used by those with the most limited experience of up-to-date methods of testing. And when we find that a star-test is capable of pronouncing *one and the same mirror on the same night by turns under-corrected, truly corrected, and over-corrected,* we see how little reliance is to be placed thereon. The writer has often had this experience when using various mirrors in the open air.

It is easy enough to see, by the out-of-focus images of a star, what is the state of correction of the mirror. A truly corrected mirror, out of focus, will give an expanded disk, uniformly illuminated except for faint traces of diffraction rings, having a clean, sharply defined edge, and a round black spot in the center. This black spot is the shadow of the flat, and it should be *the same size at equal distances inside and outside focus.*

If it is larger *inside* focus, the mirror is under-corrected. If it is larger *outside* focus, it is over-corrected. And many a time on a night when temperature was variable the writer has watched a mirror *change through all these phases* within not very many minutes, the changes of the black spot answering faithfully to those of the thermometer in the screen close by. And the changes are *not small.* A rise of 4° or 5° in the air temperature will instantly reduce the figure of the mirror from a true curve to a very much under-corrected one.

And such changes are frequent, especially on mild nights in autumn. The passage of a light cloud, the springing up of a breeze, the formation of a fog,

will raise air temperature suddenly by several degrees. And the mirror instantly responds by lowering its correction. And in the opposite event, of temperature falling sharply, the mirror goes the opposite way, the correction being raised. But this is less serious, because, as already pointed out, most mirrors are slightly under-corrected

The change, of course, is temporary, and is only due to the fact that, a mirror being a thick and massive piece of glass, and glass having a high heat capacity, its warming and cooling cannot keep pace with that of the air, but *lags behind it.* In point of fact, makers of specula, without knowing it, have been in the habit of *correcting them for a falling temperature.* If it were desired to use a speculum for daylight work, *e. g.,* for solar observation, it would be advisable to considerably over-correct, or in other words, to correct for a rising temperature. And in making a mirror for use in a climate such as that of Mexico, where temperature drops very rapidly after sunset, a figure in the neigborhood of a sphere might perform better than a paraboloid.

A striking illustration of this propensity of mirrors may here be mentioned. A 9-in. mirror made by Mr. Maurice A. Ainslie, a well-known and expert amateur speculum maker, was sent to the present writer for examination, and was found to be a little over-corrected. At the owner's request it was retouched, and the correction lowered. Some time afterwards the author was introduced to Mr. Ainslie at a meeting of the British Astronomical Association, and mentioned this mirror and its defective correction. It proved to be one which Mr. Ainslie had specially made for observing planets *in the morning twilight,* when temperature would be beginning to rise after the night, and was over-corrected because it was found to perform best in this condition.

It sometimes happens that a mirror is made of inferior glass or glass of unusual quality, and such mirrors will often have a whole set of peculiarities of their own. A thin mirror will sometimes perform quite well with one particular diameter vertical, but in all other positions give double images or reveal other signs of flexure. And twice within the writer's experience a mirror was submitted to him which *would not keep a figure.* A 9-in. mirror was on one occasion refigured *three times,* and on each occasion after a week or two was found very much under-corrected. At last the plan was adopted of strongly *over-correcting* it, and then the figure after a time came back to a paraboloid, *and stayed there.*

In concluding this part of the subject, let me give one caution to the beginner: *Do not be too ambitious.* A 6-in. mirror is quite large enough for a first essay. If not a success, as is more than probable, the loss is only a few shillings, and some time and labor. The difficulty of working a mirror increases by leaps and bounds with its aperture. Six-in. to 8-in. soon become fairly easy with some experience. But 12-in. is a tough proposition even for a skilled hand.

[The fraction $\frac{7.29}{144}$, on page 98 appears to be in error but is not. The square root of 7.29" is 2.7", the radius of the *center* of the zone, which is thus seen to be 0.6" wide in this case.—ED.]

CHAPTER VII.

Silvering

The mirror completed, it now only remains to provide its surface with its reflecting film of silver.

[See the directions for silvering issued by the U. S. Bureau of Standards, (Part VI.) These are in some ways better suited to the American worker. The method chosen is especially recommended by Mr. R. W. Porter, author of Part I. After the omission of Ellison's directions for the actual silvering process, and the substitution of Part VI for them, the text of the Ellison book continues below.—Ed.]

To Polish the Film

If we have hit off the right moment to remove the mirror from the silvering bath, very little polishing will be required. This is a great advantage, as there is always more or less risk of injuring the fragile skin of silver in polishing it. Make two pads of fine, soft chamois or washleather, stuffed tightly with absorbent cotton. Keep them in a clean jar or tin covered to exclude dust. One is to be used plain, the other covered with the very finest possible rouge. A regular speculum maker has no difficulty in obtaining the right stuff. With constant rubbing down on the tool a certain amount of rouge becomes so fine that it takes several days to settle out of suspension in water. When this is observed to be the case some of the red-stained water may be poured off into a glass dish and set aside in a warm, dry place, covered with a plate of glass. When observed to be settled clear, the water is poured off and some more of the same stuff added, and let settle in its turn. When enough sediment is seen to have collected let it remain till dry, always, of course, covered. The polishing pad is dipped in this, and takes a charge which will last almost *ad infinitum* without needing renewal.

If this method is not available we must put some dry rouge into a jar, fill up with water, and stir well. After settling, take on the finger-tip some of the red scum and froth which floats and smear it on a clean piece of glass. Dry carefully, and rub the polishing pad on it.

First rub the film carefully all over with the plain pad in small circular strokes. Then follow with the rouge pad. Very little of the latter will be needed if the mirror was not over-immersed. If it was, there will be a whitish film on it which will require a good deal of polishing to get rid of it. But even many hours' over-immersion will do no harm beyond a little extra trouble in polishing.

Once polished, leave the film quite alone. *Never attempt to get rid of tarnish by re-polishing.* You will lose far more light by *thinning* the film than you will gain by polishing it. Even when appearing very badly tarnished a silvered mirror retains nearly all its original light-grasp. Silvered glass, even at its best, never *looks* as bright as speculum metal. But appearances are deceptive. Silvered glass *looks dull* and *is* bright; speculum metal *looks bright* and *is* dull. When equally well polished a silver film reflects *about double* the light of a speculum metal surface the same size. Even when very badly tarnished, the silver film is still vastly superior to the metal at its best. This is a fact not always realized even by professional astronomers.

A Few Hints

Distilled Water.—It may not be easy to procure this in quantities sufficient for operating on a mirror of any size, but, unless one resides in a large town or near a manufacturing district, *clean rain-water* will answer all purposes if certain precautions are observed in collecting it. In the country rain-water off any clean roof will do. A glass roof is best; next best is a galvanized iron roof, and next a slated one without chimneys and free from moss and lichen. The best time to collect is on a very wet day after it has been raining for several hours. Do not dip the supply from a barrel or tank, but let it run from the eave-gutter direct into a clean vessel. Store a few gallons in clean corked bottles, replenishing the supply as occasion serves. Quart whiskey bottles answer well, as a trace of alcohol does no harm. If you are near the sea collect water only when the wind is *off the land.* Traces of chlorides are the most injurious impurities likely to be present, and they are sure to be there "when the wind bloweth in from the sea." Test a sample with a drop of silver nitrate. If no cloudiness forms in it the water is all right.

Care of Film

Next in importance to success in producing a film is success in keeping it. Two or three years are generally considered to be a good life for a film. But this can be very greatly extended, at least in the country, by suitable precautions in protecting the silvered surface. Its two enemies are *sulphur* and *moisture.* The first is only troublesome in a town atmosphere. A close-fitting cover, always on when the telescope is not in use, is the best remedy.

Moisture (the dewing of the mirror) cannot always be prevented unless the telescope is housed in a covered observatory. In the open air a rise in temperature of a few degrees, such as often happens on a fine night in autumn, will almost certainly dew the mirror. The only thing which can then be done is to close up the telescope and retire, especially as the rise of temperature will also upset the correction of the mirror for a time and play havoc with definition. But, short of a sudden rise of temperature, a mirror at the bottom of its tube, especially a wooden tube, is almost beyond the reach of dew. The flat *always* dews first.

The close-fitting cover, which every mirror should have, ought to be provided with an absorbent pad inside to take up moisture. I find the following plan so effective that I believe a film thus protected will last almost *ad infinitum,* certainly for very many years. Cut from stout pasteboard a circle large enough to fit loosely inside the mirror cell. Cut also similar circles from white blotting-paper and clean absorbent cotton. Make a sandwich of them, cardboard one side, blotting-paper the other, and absorbent cotton between, and stitch them together. Attach a loop of string to the pasteboard side. Before putting the cover on the mirror lay this pad on the face of mirror, blotting-paper next the surface of the glass, and put cover on over all. The string is for lifting off. If this pad be now and then well toasted before the fire or exposed to hot sunshine for an hour or two it will be dry enough to absorb all moisture within the cover and permit none to remain on the mirror. If the mirror ever gets dewed when

open, the pad placed on it for a few minutes will cause the dew to vanish completely. A similar pad is not without its uses inside the cover of an object-glass.

Protected in this way, I have had films in use for years and just as bright as the day they were deposited.

CHAPTER VIII.

Mounting the Mirror

If we are to be particular, and want our mirror really finely mounted, the making of a suitable cell will be an engineering job, calling for a heavy iron casting and a powerful lathe to machine it—a job for a machine shop. But the Newtonian is a very tolerant instrument, and will perform well in a mount which the most unpretentious object-glass would disdain to be seen in.

Draper and With used to sling their mirrors in a simple leather strap, with a stout board for a backing, at the bottom of a square wooden tube. And though it is desirable to have something less rough and ready than this, we can provide a very excellent cell which will hold the mirror quite securely in adjustment and also protect it from moisture and tarnish when not in use with no more elaborate tool than the plain lathe aforesaid, a set of stocks and dies for screwing, and a few hand tools.

The first item required will be a thick disk of hard wood (oak is excellent), very slightly larger than the mirror and at least 1 in. thick; more if the mirror is 8 in. aperture or over. If a sufficiently thick piece cannot be obtained, get two, and screw and glue them together, with the grain crossed. The side on which the mirror is to rest should be faced up truly flat, or, better still, have a raised ring turned on it about three-quarters the diameter of the whole thing.

We next require a strip of sheet brass about 1 in. wider than the combined thickness of mirror and wooden disk; 1-16 in. sheet will do for a 6-in. to 8-in. mirror. For larger sizes it should be thicker. This is cut just long enough to go round the wooden disk and let the ends meet, but not overlap. Cut a strip about 1 in. wide and length equal to width of large strip, and sweat it on to the joined ends. Strip and ends should be tinned and well smeared with soldering flux. Then hold in hand-vise, ends meeting, and drill and put a couple of rivets through and tap up. Reverse vise, and repeat riveting at other end. Now solder the strip and ends. Now you have a joint that will not give way for a trifle. Slip the collar so formed over the wooden disk, drill half a dozen holes round into the wood, and insert screws, and there is your cell. It requires nothing more but means of attaching to telescope tube, something to keep mirror from falling out, and a cover-cap.

To keep the mirror in, we need not go to the trouble of fitting a rim. Three small blocks, cut out of 1/4-in. sheet brass, will do. They should be spaced at intervals of 120 degrees round the inside of the cell, and either soldered to it, or, better, attached by drilling and tapping and putting a small counter-sunk screw through from outside. When thus attached, the mirror can be removed and replaced by merely unscrewing the blocks. If they are soldered, the screws holding the brass to the wood backing must be removed and the whole metal ring lifted off. As these are wood

screws, frequent removal is apt to make them loose in their holes. The method of attaching the blocks with screws is therefore to be preferred.

A simple method of attaching the cell to the tube is shown in Fig. 8. AB, CB, DB are pieces of flat iron or brass bar attached to the wooden back of the cell by screws as shown, and making angles of 120 degrees with each other. Each is long enough to extend considerably beyond the circumference of the cell, and the outer ends carry holes, the centers of which are at the angles of an equilateral triangle. These three holes fit over three screwed brass or iron rods, rigidly attached to the telescope tube. Each rod carries two nuts. One nut is placed on each rod and screwed up about 3/4 in. Then the cell is slipped over the rods, the screwed ends entering the holes until stopped by the nuts. The second nut is then screwed on to each rod, and screwed home. Obviously, any desired adjustment can be obtained by slacking off one nut and tightening the other where required. The cover-cap merely requires a piece of sheet metal cut to a circle a little larger than the cell, and a strip of length equal to the circumference of the latter. The ends of this are joined, as described for the body of the cell, and it is soldered to the circular piece. It should be an easy fit for the cell, and to secure that it is a circle it should be slipped partly on to the cell, the latter inverted on to the piece of sheet and the strip soldered while in this position, taking care not to solder it to the cell itself. A piece of the same strip, bent to a suitable shape and soldered to the middle of the cover outside makes a handle for lifting off. The whole thing is much like the lid of a saucepan.

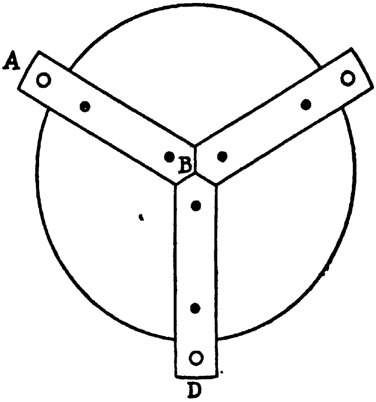


FIGURE 8

A simple method of attaching the cell to the tube—ED.

For a large cell, anything over 8 in., it is desirable to have the cover-cap convex. It can easily be made so by laying the circular sheet of metal on an anvil (failing one, the lathe bed will do) and tapping lightly all over with a hammer with a convex face. Begin in the center and go round in increasing circles to the circumference, repeating the operation till the desired degree of convexity is attained. Any spot which remains too flat should get a few extra taps of the hammer. If the sheet is brass this operation may make it brittle, and to prevent cracking it should be heated dull red, and then plunged in cold water, when it will be as soft as before hammering.

CHAPTER IX.*

The Achromatic Object-Glass

Notwithstanding all the merits of the reflector, its power, its magnificent capacity for definition, its colorless images, its compactness and economy of space, its simplicity and ease of manufacture, its cheapness, its comfort in use, there will always be a majority of the public to whom the word "telescope" means a refractor. And the refractor is certainly the most "fool-proof" form of the instrument. It has nothing about it which time can deteriorate, and its adjustments, once made, are permanent, barring accidents, meddling, or gross carelessness.

But, whereas there is an extensive literature in existence (however difficult to get at) for the aid of the amateur workman who desires to make a reflector for his own use, few indeed have ever regarded the achromatic lens as a practical proposition for the home worker. It is generally regarded as within the capacity of the professional optician only, while the high price of the necessary disks of optical glass is prohibitive to an experimenter, unless content with very small sizes.

In addition to this barrier to the amateur of limited means, the expression "calculating curves" has been a bogey to frighten away many a recruit. It seems to imply a vista of abstruse mathematical formulae, fit only for the brain of a college don.

But, as a matter of cold fact, the calculation of curves to correct *chromatic aberration* for a given focal length involves nothing more abstruse than the modicum of algebra required to solve a simple equation and sufficient arithmetic to cope with the four rules of addition, subtraction, multiplication and division and their application to decimal fractions.

The correction of *spherical aberration* does indeed call for complicated mathematical analysis. But we need not tackle it, for it has been done for us by some of the best of the world's mathematical brains, and all that we need do is to select one out of a small number of standard sets of curves. Even this is not absolutely necessary to the worker who has learned how to figure a curved surface, as will be seen later on. Now let us look the bogey in the face.

CALCULATING CURVES. FIRST STEP.

The focal lengths of the lenses of crown and flint glass, respectively, which form an achromatic pair, must be proportional to their dispersive powers.

The makers of optical glasses give, with each piece supplied, an analysis of its "optical constants." These include its refractive index, its dispersion for various parts of the spectrum, and its "medium dispersion," that is, the dispersion of the whole spectrum between the lines C in the red end, and F in the blue-green. Also the reciprocal of the last named. These are the important figures. There are some others with which we need not concern ourselves.

* **Revised for *Amateur Telescope Making* 1928, by the author.**

The refractive index is usually designated by the Greek letter μ, the dispersion by Δ, and the reciprocal of the last by the letter V.

The example appended is taken from the catalogue of Messrs. Change Bros., of Birmingham, England.

No.	Kind of Glass	Ref. Index for D.	Medium Dispersion C — F.	$V = \frac{\mu - 1}{\Delta}$	Partial Dispersion C — D	D — F	Sp. Grav-ity.
A605	Hard Crown.......	1.5175	0.00856	60.5	0.00252	0.00604	2.48
A569	Soft Crown........	1.5152	0.00906	56.9	0.00264	0.00642	2.55
A458	Light Flint........	1.5472	0.01196	45.8	0.00348	0.00848	2.93
A370	Dense Flint........	1.6124	0.01650	37.0	0.00474	0.01176	3.57
A360	Dense Flint........	1.6225	0.01729	36.0	0.00493	0.01236	3.66
A337	Extra Dense Flint	1.6469	0.01917	33.7	0.00541	0.01376	3.88

The columns headed "Ref. Index for D," "Medium Dispersion" and

$$V = \frac{\mu - 1}{\Delta}$$

are the only ones with which we need concern ourselves. They will give us all that is required for an ordinary achromatic doublet lens. The letters C, D, F, etc., refer to the dark lines in the solar spectrum which are designated by these letters, and "Dispersion C — F" means that the figure given in this column is the dispersion between the C and F lines of the spectrum. As the C line is in the red, and the F line in the blue-green, the part of the spectrum most important to vision is included between these lines. When we use these in calculating an achromatic lens, in the finished lens the spectrum will be so folded back on itself as to *bring these lines together.* The result of this is that complementary colors are combined, and the combination produces white light. Since, however, the blue end of the spectrum extends considerably farther beyond F than the red does beyond C, the combination is not quite complete, and a little blue or violet light is left outstanding.

The spectrum is more dispersed at the violet end than at the red end. This "irrationality," as it is called, leaves a little violet light outside the correction, and consequently all "doublet" lenses have a "secondary spectrum," a slight purple halo being seen around the images of bright stars, and as a border to the disks of the planets. If, however, the lens is correctly worked, and the glass is of the most suitable kind, the secondary spectrum is quite unobtrusive. The best glasses show very little, even about the image of such a trying object as the planet Venus.

To get rid of the secondary spectrum we will need a triple lens and very special and expensive glasses. Such a lens is called "apochromatic," and is a very costly article indeed. I do not propose to treat of it. The amateur worker who succeeds in making a successful achromatic doublet is entitled to think himself a very excellent optician.

We may now proceed to plan an object-glass from glasses selected, either from the above list or elsewhere. It will be convenient to follow an actual operation. I select as example one of the first lenses I constructed. It was

5-inch, and the materials were the dense flint A360 in the above list, and "optical Dutch plate." The Dutch plate was obtained from a London optical firm, because I had been struck by the excellent achromatism obtained by a combination of it with Chance's dense flint. The optical constants, as supplied by the makers, were as follows:

Optical plate:

Ref. index, 1.5195. Dispersion, C — F, 0.00906. V. 57.33

Dense flint:

Ref. index, 1.6230. Dispersion, C — F, 0.01730. V. 36.0

The crown was thus very similar to Chance's soft crown above, and the flint was their dense flint A360. The differences are no more than will usually be found in different meltings of the same composition of glass materials.

With every disk is supplied a paper stating the constants for that particular sample, which may be a little different from the list figures. The figures which we shall have to work with are the Ref. index, and those under V. The latter claim our attention first, for our first principle is that the focal lengths of our two lenses must be proportional to their dispersive powers. Now the dispersive power is found by the figure in the Ref. index column, *minus its integer 1,* being divided by the figure in the next column. The quotient is the figure in the V column. This quotient is not the dispersive power, but its reciprocal, and is used because the dispersive power is a very small fraction, while the reciprocal is a number of considerable magnitude, and so more convenient in the arithmetical processes to come.

For the benefit of non-mathematical readers we may explain that the reciprocal of a fraction is obtained by turning it upside down. That of an integer is a fraction of which the numerator is 1, while the denominator is the integer itself. Thus the reciprocal of three-eighths is eight-thirds; and that of 2 is $\frac{1}{2}$, of 4, $\frac{1}{4}$, etc.

Now V, being the reciprocal of the dispersive power, is an inverse proportion, and the following is the relationship:

Focal length of crown : Focal length of flint :: V flint : V crown, the crown having the shorter focus. Or thus:

$$\frac{f, cr}{f, fl} = \frac{V, fl}{V, cr}$$

Now to express these in numbers:

We have above, crown $V = 57.33$. flint $V = 36.0$. Therefore, a lens composed of a convex crown of 36 inches focal length, and a concave flint of 57.33 inches, will be achromatic, if composed of these two afore-mentioned glasses. But the focal length of the combination will probably not be what we require. Let us see what it will be.

The formula for focal length of a series of lenses in contact is

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} + \frac{1}{f_3} + \text{etc.},$$

if all are positive or all negative.

If some are one and some the other it becomes

$$\frac{1}{F}=\frac{1}{f_1}-\frac{1}{f_2}+\frac{1}{f_3}\text{ etc.,}$$

the concaves being negative and the convexes positive. If there is a space d between any of them, then it becomes

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2-d_1}+\frac{1}{f_3-d_2}\text{ etc.}$$

Now we can obtain from the above the means of ascertaining the focal length of our combination of a convex of 36 inches, and a concave of 57.33 inches.

$$\frac{1}{36}=.02777$$

$$\frac{1}{57.33}=.01744$$

$$\text{Difference}=.01033$$

$\frac{1}{.01033}=96.8$ inches, the required focal length.

Or thus:

$$\frac{1}{36}-\frac{1}{57.33}=\frac{57.33-36}{57.33\times 36}=\frac{21.33}{2063.88}$$

Reciprocal of this, $\frac{2063.88}{21.33}=96.76$ inches.

The slight discrepancy of .04 inch between the two results is due to our having limited the decimals in the first operation to five places. The second result, obtained by vulgar fractions, is the more accurate, though the difference is quite unimportant. We may take 97 as a sufficiently accurate result, and avoid some fractions, which will not matter. Now our answer, 97 inches, would suit a 6-inch, or 6½-inch lens very well, but would be inconveniently long for a 5-inch, for which we want about 75 inches. A simple sum in "rule of three" will now give us what we want.

97 : 75 :: 36 : 27.8 crown focus.
97 : 75 :: 57.33 : 44.22 flint focus.

We have now reached the conclusion of the first step in our calculation of curves. We have ascertained that our convex crown lens must have a focal length of 27.8 inches, and our concave flint a negative focal length of 44.22 inches, in order that the focal length of the combination may be 75 inches. We have also ascertained that the combination will be achromatic, if composed of those glasses with whose optical constants we have been dealing.

To produce an achromatic combination from two glasses taken from makers' lists, look to the column headed V. Let the focal lengths be inversely proportional to the figures opposite the respective glasses in that column.

N. B.—To avoid trouble it may here be stated that the heading of the fifth

column in the glass makers' table of constants is often misprinted. It should be, as stated above:

$$V = \frac{\mu - 1}{\Delta}$$

But Greek letters are not always to be found in a printer's font of type, and very seldom in a commercial typewriter, so various substitutes for them are frequently used, such as n for μ and D for the mathematician's Δ.

Let me again call the reader's attention to the fact that *reciprocals* are used throughout the calculations. It is not F that is the significant figure but $\frac{1}{F}$, etc.

We now proceed to the *Second Step* in the process. We have ascertained the focal lengths required. Now we want to know to what curves we must work our two glasses, in order to obtain these focal lengths. We also want to know how to provide for the elimination of *spherical aberration.*

As already stated, the latter condition is secured by adopting one or other of a few standard sets of curves, which are well known and used by all opticians. In 1915 the National Physical Laboratory published a book of *data* for object-glass construction containing suitable curves for all Chance Bros.' glasses. (Harrison & Sons, St. Martin's Lane, London, W.C.) The worker has, therefore, only to make his selection. One will naturally choose those which promise to be easiest to work and test. Two, or three at the most, will suffice for our purposes.

(I.) Crown lens: Radii of surfaces as 2 : 3.

Flint lens: One surface fits one surface of crown. The other is a plane, or a concave or convex of long radius (very nearly plane).

This gives a choice of two forms for the flint lens. If it is made to fit the shallower curve of the crown, its other surface will usually need to be another concave. If it fits the deeper curve, it probably needs a convex on its other surface. These two alternatives may be described as two different sets of curves, and they have slightly different properties, the latter giving a larger and flatter field of view, for which reason it is preferred for photographic lenses. The former is somewhat easier to construct.

(II.) Crown lens an equi-convex.

Flint lens plano-concave. Its concave surface has the same radius as either surface of the crown.

We have, therefore, three equal curves and one plane surface. This is a favorite set with many of the great telescope makers, such as Grubb, and Cooke. The only snag in it is the plane surface, as planes are more difficult to produce perfect than curves.

Messrs. Chance Bros. have a special pair of glasses which will give perfect achromatism with any three equal curves and a plane, one of the curves being the concave of the flint. These are their "Telescope Crown," 3289, and Dense Flint, Type 361. The optical constants of these are, respectively:

Crown Ref. index, 1.5153. Mean dispersion, .00858. V. 60.0.
Flint Ref. index, 1.6214. Mean dispersion, .01724. V. 36.1.

These are very simple figures to work with. The crown also being equi-convex, and the flint having only one curved surface, the calculations are reduced to a minimum; so that, except for the difficulties of the plane surface, the second set of curves is the most suitable for the amateur worker to attempt. We will return to it later on.

At present we are engaged on the 5-inch optical plate and dense flint, and have ascertained that the crown lens is to have a focal length of 27.8 inches, with radii of the surfaces in the ratio of 2 : 3.

The formula connecting curves with focal length is:

$$\frac{1}{f}=(\mu-1)\left(\frac{1}{r_1}+\frac{1}{r_2}\right)$$

But in the present case $\frac{r_1}{r_2}=\frac{2}{3}$ so that $3r_1=2r_2$

therefore $\left(\frac{1}{r_1}+\frac{1}{r_2}\right)$ becomes $\frac{5}{2r_2}$ and we have

$$\frac{1}{f}=(\mu-1)\,\frac{5}{2r_2}=\frac{5\,(\mu-1)}{2r_2}$$

Substituting for f and μ their values, which we know (27.8 and 1.5195), we have

$\frac{1}{27.8}=\frac{.5195\times 5}{2r_2}=\frac{2.5975}{2r_2}$ therefore $27.8=\frac{2r_2}{2.5975}$ and $2r_2=27.8\times2.5975=72.21$.

r_2 therefore $=36.1$ inches. But r_1 is two-thirds of r_2, therefore $r_1=24.06$ inches.

The radii of the curves of our crown lens are therefore 36.1 and 24.06 inches, respectively.

For the flint we proceed in the same way. But we have one of its curves already, as it is to fit the crown. This is not necessary, but very convenient, and may be labor-saving, for we can grind one glass with the other, and thus form two curves at once.

If we make the flint concave to fit the deeper side of the crown, we shall find (with a flint of such density as we are using) that the other surface will have to be a convex, as noted above in treating of the second modification of the first set of curves. This would make an excellent lens, but it would involve the treatment of *three* convex surfaces. We can test a concave by the shadow method, but not a convex, and as our present object is to make the process as simple as possible, we take the shallower curve of the crown to fit the flint. The first surface of the flint is therefore to have a concave curve of 36 inches radius. What must the other be?

The formula is as before:

$\frac{1}{f}=(\mu-1)\left(\frac{1}{r_1}+\frac{1}{r_2}\right)$. The focal length is to be 44.22 inches.

Substituting

$$\frac{1}{44.22} = .623\left(\frac{1}{r} + \frac{1}{36}\right) = \frac{.623\,(36 + r)}{36r}$$

Therefore $36r = 44.22 \times .623\,(36 + r) = 27.55\,(36 + r) = 991.8 + {}^{*}27.55r$ and $36r - 27.55r = 8.45r = 991.8.$

$$r = \frac{991.8}{8.45} = 117.3 \text{ inches.}$$ This is the radius of the fourth surface.

We can now write down the complete specification for our 5-inch object-glass.

Crown lens	1st surface, 24 inches 2nd surface, 36 inches	convex.
Flint lens	3rd surface, 36 inches 4th surface, 117 inches	concave. concave.

Crown focus, 27.88 inches Flint focus, 44.22 inches	Combination focus = 75 inches.

We have neglected the decimals in the radii because they are so small that they could hardly be given effect in practical working. There is also another reason, viz., that the above formulae are only exact for the theoretical case of a lens *of no thickness.* The thickness introduces a small error, by making the crown lens weaker (of longer focus) than computed. It has no effect on a lens with one plane surface, and therefore the flint lens, being nearly plano-concave, is left unaffected. The net result is to make the finished lens, *if worked exactly as computed,* slightly over-corrected for color. The *if,* however, is a big one; and, all things considered, it is better to get as near to the computed curves as our skill will enable us.

For such lenses as we are working with, where the focal length is about 100 times the thickness, the error is very small. It is troublesome to correct for thickness, and opticians commonly neglect the small error. Many lenses made by the big makers are a little over-corrected in consequence. Others are remedied by mounting the lenses, not in contact, but separated by a distance ring. This separation has the effect of lowering the color correction, and the thickness of the ring can be adjusted till the correction is perfect. For terrestrial and look-out purposes a slightly over-corrected lens works well, for the erecting eyepiece usually employed is under-corrected and compensates the object-glass.

We will now glance briefly at the other set of curves given above, for Chance's Telescope Crown, and Dense Flint Type 361.

As stated, these give perfect correction with three curved surfaces of equal radii, and one plane. The writer constructed several object-glasses with these

* Note: If this figure is greater than the coefficient of r on the left of the equation, at the next step this term will become *negative.* This will signify that the curve of the fourth surface will be of opposite sign to the third; i. e., in this case *convex.* If the coefficients come out equal, it will be plane.

some five years ago, and found them answer admirably. Two of these were glasses of 6 inches aperture, and 91 inches focus, and this is a very convenient size to take as an example.

Let us consider how the formula for focal length will work out.

The constants are:

Telescope Crown. R. index, 1.5153. V. 60.0.
Dense Flint 361. R. index, 1.6214. V. 36.1.

By the principle used in our first step above, a convex crown of 36.1-inch focus, and a concave flint of 60-inch focus, made of these glasses, will be achromatic. Its focal length, too, will be somewhere near 90 inches, which will do well for a 6-inch.

$$\frac{1}{36} - \frac{1}{60} = \frac{60-36}{60 \times 36} = \frac{24}{2160}$$

Reciprocal $\frac{2160}{24} = 90$ inches.

Having neglected the decimal .1 for the sake of simplicity in calculation, our crown lens will be a little too strong. It will therefore do no harm to allow a little for this, or else do the calculation again, using the amended figure, 36.1. But it is quite possible that the actual glasses supplied may differ slightly from the list constants; so we will leave it at that. The fault is on the right side in any case.

Now let us have the old formula again: $\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$

But since r_1 and r_2 are this time equal, it becomes $\frac{1}{f} = (\mu - 1)\frac{2}{r} = \frac{2(\mu - 1)}{r}$

Now if $\mu = 1.5$, then $\mu - 1 = 0.5$ or $\frac{1}{2}$, and $\frac{2(\mu - 1)}{r} = \frac{1}{r}$.

So $\frac{1}{f} = \frac{1}{r}$ and $f = r$. Hence an equiconvex lens made of glass with a refractive index of 1.5 has a focal length equal to the radius of either surface. A plano-convex lens of the same glass has a focal length equal to twice its radius. This is useful to remember. Our telescope crown, however, has a refractive index slightly greater than 1.5. In this case $\mu - 1$ will be 0.5153, and twice this is 1.0306.

So $\frac{1}{f} = \frac{1.0306}{r}$ and $f = \frac{r}{1.0306} = \frac{36}{1.0306} = 34.93$, or very nearly 35 inches.

In the case of the flint lens there is only one curve.

So $\frac{1}{f} = \frac{\mu - 1}{r} = \frac{.6214}{r}$ and $f = \frac{r}{.6214} = \frac{36.1}{.6214} = 58.9$.

Though these results do not look like mathematical accuracy, they are near enough for our purpose. The reason of their seeming roughness is that the figures given for V are approximations to one decimal place. The crown V above, for example, is 60.06. 60.0 is the makers' round number, which is near

enough to work to. In working the same glasses I used 36 inches as my standard, and getting as near it as was practicable, I obtained excellent results, the combined focal length working out at 91.5 inches.

The equiconvex crown has some important advantages, both in working and use. It can be reversed without detriment to its spherical correction, if properly figured. For the optician, who uses cast-iron or brass tools, it has the advantage of requiring only one set of tools for the two surfaces. And it would be quite possible, with this set of curves, to *dispense altogether with calculation,* and work to the V figures; giving the crown two surfaces of 36 inches radius, and the flint one. This would give a lens of 90-inch focus, and would be very fairly well corrected for color. If not quite satisfactory, it could be separated a little if over-corrected, or the fourth surface given a *very* slight concavity, if under-corrected. The dimensions above would be right for a 6-inch. For a 3-inch the figures could be halved; and for other apertures in proportion.

Lest the testing of the plane surface should be a difficulty, refer to Figure 10. Here the simple set-up quite clearly shows the method of testing an object-glass by means of a perfect plane. Obviously, a plane can be tested by means of a perfect object-glass in the same manner. For the optician who has many object-glasses to work, a true optical plane of considerable size is a necessity. The amateur who cannot obtain one is advised to confine his attention to set of curves No. (I).

It may not be amiss to note here that, in all ordinary object-glasses, the crown lens always "leads," that is, it is nearest to the object, or is the outer glass in a telescope. A few German opticians put the flint lens leading, but this requires a reconstruction of the whole scheme of curves. British and American glasses have the crown the outer. It is rather a peculiar circumstance that seamen seem to have a preference for turning the flat side of their glasses out. The writer has examined numerous "spy-glasses," at coast-guard and life-boat stations and elsewhere, and always has found their object-glasses wrong side out. Needless to say, the effect on their performance is anything but beneficial.

The surfaces of an object-glass are always numbered from the front curve backwards; first, second, third, fourth; the first being the outer. In the case of a triplet there would be a fifth and sixth.

CHAPTER X.

Practical—Shaping and Grinding

It will not be necessary to recapitulate the processes of coarse and fine grinding, which have already been described in dealing with speculum making. Everyone who has made a concave mirror is already familiar with the production of concave and convex spherical surfaces by grinding two equal plane disks of glass upon each other. The same process which produces the shallow curves of telescopic specula need only be carried a little further to produce the deeper curves of an object-glass. There is only one important difference, viz., that now we have to produce curved surfaces *on both sides* of a disk of glass, and these surfaces must be correctly centered with respect to each other. In other words, the edge of the lens must be exactly the *same thickness all round*. To secure this we require a pair of *micrometer calipers*. The ordinary calipers are not at all delicate enough for the extreme accuracy required. An error of 1/1,000 inch in the thickness of the edge will produce a most deleterious effect on the images produced by the finished lens.

The optical glass we require is sold either in disks or in square slabs. In the latter form it is considerably cheaper, but we have the trouble of cutting out the disks. This operation is not so difficult as it looks. The corners of a square slab of glass are quite easily sawn off with a piece of hoop-iron and a little No. 80 or 120 carborundum and water. The saw-cut is begun on one side and carried nearly half-way through, then begun again on the other side, and when the cuts have come near enough the corner is gripped in the vice and broken off. In this way the square is made an octagon. The angles of the octagon can then be further blunted with the carborundum wheel or grindstone, and finally the piece is cemented with pitch to a pair of wooden handles mounted in the lathe and edged circular, and reduced to the required diameter in the same way in which the disk for a mirror is edged, that is, with a band of hoop-iron attached at one end and bent up for a handle at the other, the band nearly encircling the disk; and using No. 80 carbo. followed by finer sizes.

Two disks, the crown and flint, will, of course, be prepared, and these must be of *absolutely exactly* the same diameter. It is a good plan to cement them together and edge both at the one operation. But care is necessary not to damage them in parting them again. Also, the edges should be bevelled as a precaution against chipping by accidental blows. Two or three disks of ordinary plate glass ¾ inch thick or thereabouts should be edged also to the same diameter, to serve as tools.

If it has been decided that the second and third surfaces, being of the same radius, shall be made to grind each other, thus saving one whole operation of rough and fine grinding, we now cement the crown disk to a thick disk of wood, as we would the glass tool for a mirror, but with this difference, that the block should be of considerably smaller diameter than the glass, about two-thirds of it, and it is provided with a disk of sheet-iron of a diameter a little greater than the glass, which is screwed to the wooden disk concentrically for attachment to the barrel. The glass is, of course, cemented with pitch and

the sheet-iron is attached to the top of the now familiar barrel by means of screws. The object of the arrangement is twofold. The crown disk is not very thick, and if attached to a bed of pitch covering its whole surface would infallibly be flexured. And later on, when the other side of the crown is being ground, it will be necessary to have *room on both sides* of it to admit the micrometer calipers to gauge the thickness of the edge.

We are now ready to commence operations, and having provided the flint disk with a wooden handle, as we do a mirror, and placed a basin of water and a handful of absorbent cotton handy on the work-bench, we proceed to arm the disks with a sprinkling of No. 80 carborundum, dip the flint in the water, lay it on the crown, and grind with the mirror-maker's threefold motion.

It is to be noted that the handle by which the flint is held should be carefully centered. This is not absolutely necessary in grinding a mirror, but essential in making a lens whose two surfaces have to work with each other. About two or three hours, according to the size of the disk, will probably suffice to bring the curve near the required depth. As the grinding progresses the curve is checked from time to time, as in the case of a mirror, by wetting the concave surface and testing it with a light. (See Chapter II).

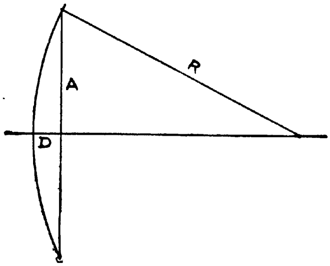


FIGURE 9

The radius $R=\dfrac{A^2+D^2}{2D}$

It is necessary to stop the rough grinding while the curve is still a foot or more longer in radius than we require. Carefully clean the disks and barrel of all trace of the rough carborundum, throw away the absorbent cotton and water in the basin, and get a fresh lot, and proceed to the next carborundum grade, 220. With this the curve is brought very nearly to the exact depth required. To gauge its progress more exactly than with the candle flame, we now use the modification of Foucault's pin-hole lamp, which we used for testing mirrors at the same stage. Opticians use a spherometer to read the curve of spherical surfaces. This is a small instrument with three feet, either pointed or ball-tipped, the three occupying the angles of an equilateral triangle. In the center is a fine micrometer screw, with a point which can be screwed down to touch the surface on which the feet rest. The radius of the curve as obtained from its reading, is shown in Figure 9.

The reading of the micrometer screw gives D, and A is the distance from the screw point to each foot. The spherometer is an expensive little instrument if accurately made, and the method described above of obtaining the radius of a concave curve is just as accurate in practice, if not more so. To measure a convex we measure the concave tool which ground it, and as the fit of the two at the end of fine grinding is very exact the method is quite satisfactory.

The directions for fine grinding given in the section on mirror-working are in no respect different from the methods to be used with a lens, and they need not be here repeated. The only difference is that, as the convex tool in this case is the crown lens itself, it is not advisable to use it to form the pitch tool or for polishing the corresponding concave. Any old glass tool of approximately the same curve and size can be used, or, failing a suitable one, a disk of hard wood can be turned up to near the curve, and the pitch tool formed on that. But it is well to postpone polishing any surface till all are fine-ground.

Having finished fine-grinding the second and third surfaces on each other, we now proceed to rough out the first surface. The crown is detached from its block, turned over, and re-cemented flat side up. One of the pieces of plate glass prepared for a tool is cemented to a handle, and the process goes on as before. But this time we must bring the *micro-calipers* into play. As the curve approaches the desired depth (ascertained by measuring that of the tool) we must try the calipers round the edge of the lens at frequent intervals. If any part of the circumference shows excess of thickness it must be reduced by temporarily stopping the operator's walk around the barrel and working with increased pressure on the thickest part for a few minutes at a time till the calipers show equality all round. Of course, before applying the calipers the lens must be washed and dried. No grit must be present, and a wet surface is very undesirable.

As the *thickness* of the lens enters into the formula for focal length, it will be necessary to pay attention to this point. One-half inch is a convenient thickness for a 5-inch to 6-inch lens (crown). If the slab to begin with is just a little more than this, it will come very nearly right when finished. If not, perhaps the simplest way will be to compute the curves at first for a thickness a little less than that of the slab. Otherwise it may be necessary to grind with very short strokes, in order to prevent the curve reaching the desired depth before the thickness is sufficiently reduced, which would waste a lot of time and labor.

When the fine-grinding of the first surface is complete, we turn to the fourth surface. As this is a shallow curve, working it resembles in every respect the making of a mirror, except that the micro-calipers must be busy checking the exact equality of thickness all round the edge. The handle (cemented to the center of the third surface) must be carefully centered. Grip it in a three-jaw chuck in the lathe, and rotate it and the disk while the pitch is still soft, and correct any lack of truth in its running by pressure in the direction required. It will be nearly impossible to keep the third and fourth surfaces truly centered with respect to each other if this handle is not in the center of its disk. When completed, or better, just before the last stage or

two of fine-grinding, it will be well to see that the bevel placed on both disks is not ground entirely off. If it is it should be restored, or an ugly chip may result from any slight accidental jar.

Polishing

Once more the mirror-maker finds himself on familiar ground, with some differences. The pitch polishing tool is formed, just as in the case of a mirror. It is, however, less necessary to be careful about the facetting. For sizes of 4 inches and under it is not necessary to facet at all, or two channels at right angles to each other, dividing the tool into four unequal parts will be sufficient. Above 5 inches the tool may be divided into squares of $1\frac{1}{4}$-inch side, the center of tool being in the corner of a square, precisely as is done when preparing a polishing tool for a mirror.

The convex surfaces of the crown lens may conveniently be polished first. No question of their figure can arise at this stage of the proceedings, as it is impossible to test it. It will, however, be advisable to use a pitch tool well on the hard side to avoid "turned edge," which is just as formidable in a lens as in a mirror. Also it will do no harm to cut away a little of the center of the tool, preferably in the shape of a star; as in polishing a convex the center is apt to get more than its share, with the result of flattening the curve there. It is no harm at all if a hump in the center is the result, as it is very easily removed later on.

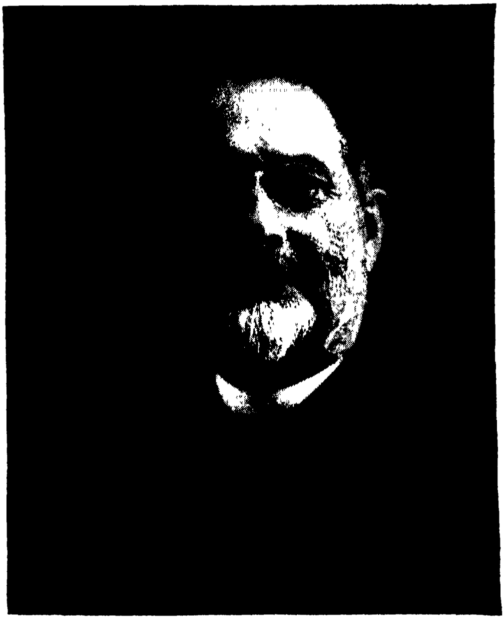
The polishing should be continued till no abrasive marks are visible on examining the edge of the lens with a microscope. Nearly all makers scamp their polishing more or less. It is a rare thing to find a lens, even by the great masters of the art, one or more surfaces of which do not show, when examined with a low power on the microscope, thousands of tiny abrasive pits. Each of these is in practice a minute opaque spot, and the presence of thousands of them has two results, both bad for the performance of the lens. It reduces the transparency, and consequently the light-grasp. And it introduces diffraction effects which scatter light and illuminate the background of the field of view.

The crown lens may be polished either face up or face down. Face down is probably preferable, as the small handle cemented to the glass for holding by, is more easily detached and refixed without danger, than the block underneath would be, and there is less risk of flexure.

It must always be borne in mind that the crown lens is the thinner of the two, and not half the thickness, relative to its diameter, that a mirror would have. Fortunately, flexure must be much greater, to affect perceptibly the performance, in a lens than in a mirror. The reason is that if a lens is flexured, the two sides are bent *opposite ways*. Consequently, the flexure of one side compensates that of the other. Sir H. Grubb has shown that in the theoretical case of a lens with no thickness, flexure, however great, would have no effect, for the compensation of one side by the other would be complete. As our lens, however, must have a thickness we must see that flexure is avoided as far as possible.

Having polished the convex surfaces, we now proceed to the more familiar task of polishing the concaves. The third surface, the deeper concave, should be done first. Its figure can be roughly checked by the shadow test, though, owing to its short radius, it is impossible to test it with delicacy because the image of the pin-hole must be thrown far enough from the optical axis to distort the shadow very appreciably if it is to be brought within reach of examination. But it can be tested well enough to ascertain that its figure does not depart very markedly from a sphere.

The fourth surface can be polished and figured usually just like a mirror. But we need not strive after any definite figure at present. It will suffice to see that it does not become a deep hyperbola. It is best to have it somewhere near a sphere. If it should by chance turn out to be a pronounced oblate spheroid, let it remain so, as the final correction will be all the easier. But do not tolerate any irregularities. Humps or hollows in the center, or a turned down edge, should be eliminated as carefully as from a mirror, especially the hollows.



The author.

CHAPTER XI.

Testing and Figuring

When the polish of the four surfaces is complete the lens can be assembled and tested for focal length. If the curves have been worked accurately as computed, this should come out very close to the computed focus. But if thickness was not taken into account in computing, and was compensated for afterwards by rule of thumb, we must expect the actual focus to be shorter, probably by some inches.

We can also test for performance, if we have a cell ready in which to mount the lens. If not, we must wait till this is made. This is a job for the lathe and the brass-finisher, but the amateur who is capable of constructing his own object-glass will certainly not be beaten by the cell.

But when assembled and mounted we must not expect the lens to be ready for use in the telescope. In fact, the hardest part of the job is still before us. The set of curves chosen was, to be sure, one of those computed to correct spherical aberration. But it is a thousand to one that it does not. And for a very simple reason. The tables laboriously computed to remove spherical aberration all assume that the curves are truly spherical. This, as a matter of fact, they never are, except by accident. We can figure concave surfaces to any curve our skill is equal to. But of the figure of our two convex surfaces we know nothing at all. It may be anything, ellipse, sphere, parabola, or hyperbola, or a mixture of all four. All we can do is to try the lens and figure one or more of its surfaces according to what we see. And, fortunately, it is possible to correct the errors of the surfaces we cannot test by figuring one of the surfaces which we can test.

If there is an error in the convex lens which we cannot remove it is possible to compensate it. For example, if the center of the convex lens is too flat, making the focal length of the corresponding part of the object-glass too long, we can compensate this by making an equal area of the center of the concave lens also too flat. Or, if the whole lens, though regular in correction, proves under-corrected for spherical aberration (*i.e.*, the focal length becomes greater as we pass from margin to center) we can compensate it by figuring the back of the flint lens to a more or less pronounced oblate spheroid. If, on the other hand, the whole lens is over-corrected, we figure the back curve to a hyperboloid. The under-corrected condition is far more likely to occur, and it is for this reason that it is well to leave the preliminary figure of the fourth surface a sphere or an oblate spheroid. It is very easy to convert it into a hyperbola if necessary.

If the errors found on trying the lens are of large amount it may be necessary to figure all four surfaces to eliminate them. But if we can ascertain that an observed error is due to some one surface, it will of course be best to refigure the offending surface itself. How, then, can the offender be located? This is where the advantage of having as few convex surfaces as possible comes in. When we have two concave surfaces, we can ascertain by direct

inspection with Foucault's lamp and knife-edge if either of these is at fault. If not, then the fault must be in one or other of the convexes. To ascertain which of them is at fault is easy with the set of curves we have been working—viz., one having the second and third surfaces in contact. If a transparent liquid having nearly the same refractive index as glass be placed between these surfaces, they are optically abolished, and the lens behaves as if it were a solid one having only two surfaces. Therefore, if the defect be in the second surface it vanishes. If it still is there, it can only be in the first surface. Thus the offending surface is tracked down and its errors can be corrected *in situ*. Liquids suitable for the purpose are Canada balsam, castor oil, and glycerine.

Now as to the testing of our objectives. Till quite recently the only way of testing an objective was by actually trying it on a star. Many an optician cast longing looks on the ease and simplicity of Foucault's shadow test, by which mirrors can be figured so accurately, and longed for something equally simple for guiding his hand while figuring the surfaces of an object-glass. The writer believes he was the first to devise, and he certainly was the first to publish, a simple means to this desirable end. Let us recall the principle of Foucault's apparatus, referring to Chapters II and III.

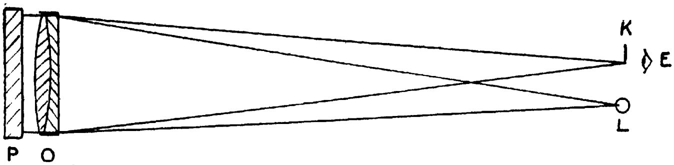


FIGURE 10

It is clear that we can test an objective as there described only by putting the lamp at one side of it and the knife-edge at the other. Also the distance of each from the lens must be twice its focal length. So, whereas a mirror requires a straight line of twice its solar focal length for testing it in, an object-glass will require four times its focal length. A 4-inch would therefore require 20 feet, a 5-inch 25 feet, etc. And, moreover, when so tested, the results would be unsatisfactory. For an objective is corrected for parallel rays, and the rays from a point two focal lengths distant are far from parallel In the case of a mirror this objection is got over by the simple little formula $A = \frac{r^2}{R}$, as explained in the chapter on zonal testing. But in an object-glass there is no R, or, rather, there are four R's, all different, and none of them having any relation to the focal length of the double lens.

The idea occurred to Professor Fullan, of the Alabama Polytechnic Institute, U.S.A., that the testing of a mirror could be simplified by placing the Foucault lamp at the solar focus of the mirror instead of at center of curvature, so that the returning beam would be parallel, receiving this parallel beam on a plane mirror which returns it to the concave, from which it is again

returned convergent to the eye and the knife-edge. In this way the necessity for using the $A = \frac{r^2}{R}$ formula disappears and the surface of a truly parabolic mirror presents the easily identified flat appearance which in Foucault's method characterizes the sphere. But the arrangements needed are awkward and complicated, and the method is not likely to supersede Foucault's. But in examining Professor Fullan's apparatus it flashed across my mind that this was just what was wanted as a workshop method for testing object-glasses. It did not take many minutes to set up the apparatus. A plane mirror in front of the object-glass, as close to the first surface as possible, Foucault's lamp and knife-edge at the solar focus of the lens, and the outfit is complete, as in Figure 10.

The light from the pin-hole lamp, L, at the solar focus of the lens, O, falls on the lens, and, after passing through it, issues as a parallel beam. As a parallel beam it falls normally on the plane mirror, P. It returns from the mirror still parallel, re-enters the object-glass parallel, as a beam from a star would, and is by it converged back again to the solar focus, where it forms an image of the pin-hole. As before in the mirror test, a slight *ecart* of the lamp to the left diverts the image to the right sufficiently to enable an eyepiece, or the eye itself, to receive it. If the objective is perfectly corrected, the divergent beam becomes parallel without aberration, and the parallel beam again becomes convergent without aberration, and when the knife-edge is made to cut across the beam exactly at its focus, the eye just behind it sees the illuminated lens darken evenly all over, with the flat appearance of a truly spherical mirror under Foucault's test. But if the object-glass under test has defects in its correction, every such defect is doubled, because the light passes through the lens twice.

The chromatic correction, as well as the spherical, is tested by this useful device, by examining the image with an eyepiece. On pushing the eyepiece inside, or drawing it outside, focus, the colors of the secondary spectrum are seen, as when the image of a star is examined in the same way in the telescope. Only in the apparatus the secondary spectrum, like all other outstanding defects, is doubled. In optical apparatus the name of "collimating lens" is given to a lens whose office is to render a divergent beam parallel before it enters an objective. We have therefore given to this method of testing the name of the Autocollimation Test, because the objective under test acts as its own collimator.

Now let us suppose that our objective is under-corrected for spherical aberration, as it is almost certain to be; because, in the absence of any check on the figure of the convex surfaces, these surfaces get almost invariably too much polishing in the center, with the result that the curve is too flat there and the central focus too long. This will reveal itself in the auto-collimation test as a forward bulge or hump towards the observer. Whereas, if the lens be over-corrected, it will look hollow in the center, bulging away from the observer. If the under-correction is not great, it may be remedied by working the back of the flint lens to a similar hump, making it an oblate spheroid, in fact. If too great for this, we must find which surface is at fault and try to

remove the flat center by working with a tool with the center more or less cut away.

If there is any uncertainty whether a visible defect is due to a hill or a hollow, the point can be cleared up by a very neat method given by Sir Howard Grubb in a paper in *Nature*. Rub the bare hand over the glass at the spot affected. The warmth communicated by the hand to the glass causes a slight bulge thereon. Now test again before it has time to cool. If the defect was due to a hill, it will be aggravated; if to a hollow, it will temporarily disappear, and you can watch it come back again as the glass cools. A hollow must be treated by polishing with a tool which acts on the rest of the surface and leaves the hollow spot alone. The remedy for a hill is obvious.

Far more difficult to treat than hills and hollows is a turned-down edge, a defect which nearly all object-glasses by second-rate makers suffer from. It is indeed the *bete noire* of the optician, always ready to show its objectionable presence on every surface polished with pitch. It is on account of the ever-present fear of turned edge that it is always advisable to keep pitch too hard rather than too soft. And one of the advantages of a slight admixture of beeswax in polishing pitch is that it greatly reduces its tendency to turn an edge. It is much easier to prevent turned edge than to cure it. Therefore, in polishing our surfaces we took care to use pitch on the hard side, and to finish our back surface if possible with a turned-up edge, as this will neutralize a possible turned-down one on another surface. But if, in spite of all, we find a turned down edge showing in the auto-collimation test, we must polish at our convex surfaces with hard tools, and tools slightly less in diameter than the lens, till the defect is eliminated. It often happens that we get rid of it partly with much ease by working at one surface, but cannot get any further. The best plan then is to attack the other in the same way.

The operator who has the skill to figure a mirror successfully will have no real difficulty in overcoming the very analogous problems presented by an object-glass, especially as his task is rather simplified than complicated by the four surfaces, since he can, to a considerable extent, play off one against another. Another point in his favor is that the so often troublesome edge is cut off by the cell, so that he is not bound to be so particular that his curves should be exact up to the extreme edge. It may also be mentioned that the circle by which the light leaves the object-glass is necessarily smaller than that by which it enters it; therefore, the cell flange may be a little deeper at the back than at the front without cutting down the clear aperture. A narrow defective zone on the back surface will thus be kept out of action altogether.

It will be seen also from the foregoing that, so far as the practical optician is concerned, the careful computing of curves to cure spherical aberration is waste of time. It is not too much to say that the operator who is skilled in figuring might safely undertake to produce a perfect object-glass with any set of curves whatever, provided chromatic aberration was corrected; trusting to figuring alone to correct the spherical aberration. The writer has seen a 3-inch object-glass whose curves, if spherical, would only define with the convex lens in front, so manipulated that it would define perfectly with

the flint lens leading, and not in its normal position. To such a length has skill in figuring been carried, that some amateur mirror and lens makers can juggle with curves to an almost unlimited extent, producing at will any desired form of concave surface, from the most extreme oblate spheroid to the most extreme hyperboloid.

The detection of a turned edge when using the auto-collimator, is similar to the corresponding operation on a mirror, with one difference: When examining the image of the pin-hole with an eyepiece, it is the disk outside focus which shows a hairy edge in the case of an object-glass with a turned-down edge. With a mirror, it will be remembered, it was the disk inside focus which was affected. When testing an object-glass on a star in the telescope it will be the same; and one of the first things to be noted will be the out-of-focus image of a bright star, outside focus. If this is circular and fairly sharp in outline, and its edge is slightly green in color, a favorable judgment of the lens may be formed at once, as the commonest defect of an object-glass is not present. Inside focus the expanded disk should be similar to what it is outside, except that the margin should be slightly purple instead of green. If the lens is properly corrected for both spherical and chromatic aberration it will come sharply to focus exactly at the point where the purple disappears and the green appears, or *vice versa*. At this point the image in a good lens is very nearly colorless.

When, satisfied with our workshop tests, we come to try our objective on a star it will be necessary first to see that the lenses are an easy fit in the cell, and that the counter-cell is screwed home, but not tight. The lenses should rattle very slightly when shaken. Then the cell is screwed home into its object-end and a look taken at a bright star with a moderately high-power eyepiece, say, 1/4 or 1/8 inch. The first view will not be a good one, as the objective will be "out of square." The star will have a flare on one side. With the type of objective we have been making, to remedy this the side of the objective next the flare must be pushed in or the opposite side pushed out. Let the screws holding the object-end to the tube be loose enough to enable the end to move when moderate force is applied. Place a short piece of wood against the cell and tap it in the required direction with the wooden handle of a screw-driver or other convenient object. If the cell has pull-and-push screws, so much the better.

When the image is as symmetrical as possible, put on the highest eyepiece you have, and focus carefully, and note the appearance of the star-image. It should be a tiny, circular dot, surrounded by one or two very fine rings of light. If these rings are too numerous, or are thick and coarse, spherical aberration is not fully corrected. If they are thicker on one side of the image than the other the squaring is still defective, and the side of the objective next the thick part must be pushed in a little more.

A slight movement of astigmatism is very often found in an objective when first tested, after all adjustments have been made as perfectly as possible. This shows itself by the image, a little out of focus, being not circular, but slightly oval, the major axis of the oval being one way inside focus, and at

right angles to that outside focus. The cause of this is slight flexure, probably present in both lenses. To remedy this the lenses must be rotated on each other a little at a time until a position is found in which the defect vanishes or is reduced to the smallest possible amount. When this is found, the edges of the lenses must be marked so that they can always be placed with certainty in their right relative position.

Some makers notch the edges and solder a pin into the cell to fit the notch, so that if removed for any purpose the lenses cannot be replaced except in the right way. Rarely indeed is a lens so perfect as to be quite indifferent to the positions of the components with respect to each other. If the oval images cannot be made to become circular in any position, one or other lens is seriously flexured, and it may be necessary to re-grind it. But this should not happen if proper care was taken in supporting the lenses correctly in the original working.

If badly astigmatic, the image at focus will be a cross instead of a small disk or a point. For this the only remedy is to return to the last stages of fine-grinding, and use greater care.

CHAPTER XII.

Mounting the Lens

The worker who has successfully finished an object-glass or mirror will, before he can use it, be obliged to provide it with a mount or "cell". An object-glass cannot even be tested accurately until fitted into its cell. It is therefore desirable to make this as soon as the preliminary polishing of the four surfaces is completed, before beginning the delicate work of figuring.

The making of an object-glass cell will be a nice little exercise in brass-fitting, just the sort of job that the amateur lathe-man enjoys. We require first of all a suitable set of castings, unless the lens to be mounted is quite small, not over 2¼-inch aperture, in which case a piece cut from a heavy brass tube of the requisite size may be used, and will save the trouble of machining a rough casting. But for a lens of any size castings are indispensable. If any quantity of brass scrap of fair quality is lying about, and a friendly founder can be got to melt it down, it will save expense.

We will require at least two castings, perhaps three. One of these will be for the body of the cell, a second for the counter-cell or screw-ring which confines the lens in the cell, and the third for the "end", the piece which fits

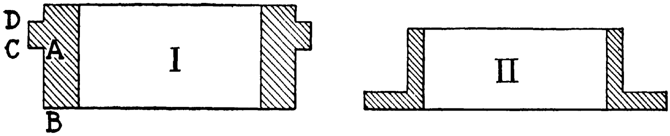


FIGURE 11

I is a cross-section of pattern of cell casting. If the portion A B be made deep enough, a ring turned off the lower part can be used for the counter-cell, saving a separate casting and pattern. II is a form of casting for an adjustable cell. Two castings from the same pattern will serve—one for the cell, the other for the "end."

on to the telescope-tube and into which the cell screws. It is preferable, however, to make the pattern deep enough to enable us to turn off a ring from the bottom of the castings after the preliminary machining, and to use this for the counter-cell, saving the making of a very thin and flimsy pattern which would be liable to break or warp in the moulding. Figure 11, I, shows the form of pattern required for the cell. By making the portion AB a little deeper than shown there will be enough metal in the casting to admit of turning off the lower portion and using it for the counter-cell. A similar pattern, but lighter, and without the flange CD, will serve for the "end".

A good lathe is, of course, requisite for dealing with the job, and the better the lathe the easier it will be to turn out a satisfactory article. But an ordinary plain lathe with 3-inch to 4-inch centers can be made to serve if the worker is ingenious; and if he can use "chasers" nothing else is required. The writer's tool is a plain 4-inch lathe provided with the usual

chucks and face-plate, but with an extra in the shape of a fine 5-inch 3-jaw scroll chuck, which is most extremely useful. To adapt this machine for screw-cutting the following additions were made to it: Firstly, on the driving-shaft a 2-step pulley of hard wood having one step double the diameter of the other, one 3-inch, the other 6-inch diameter, to bottom of groove, is fitted. This slides freely along the shaft, and can be clamped to it at any point by a set-screw. Secondly, behind, and rigidly attached to, the hand-wheel which operates the back-center screw is another wooden pulley $2\frac{1}{2}$ inches diameter to the bottom of groove. A couple of thin gut driving belts, crossed where they pass between the bars of the lathe-bed, connect the shaft-pulley with that on the hand-wheel when required, and can be attached or detached in a moment. In this way the hand-wheel can be driven at the rate of 6 turns to 5 of shaft, or 12 turns to 5. Now the lowest gear of mandrel to shaft is 4 to 1; so the speed of the hand-wheel to mandrel is 6 turns to 20, or 12 to 20—i.e., $3\frac{1}{2}$ to 1, or $1\frac{2}{3}$ to 1. But the pitch of hand-wheel screw is 9 threads per inch, so the mandrel makes 30 turns, or 15 per inch traverse of the poppet, according to which step is engaged. The next speed on mandrel pulley is $5\frac{1}{3}$ to 1, which gives for 15 and 30, 20 and 40 respectively, so that we have 15, 20, 30 and 40 threads per inch which can be cut. These are sufficient for most things in telescope work.

When a screw is to be cut the back center is removed and into its socket is placed a fitting which projects forward across the T rest and engages the chaser when held in position for cutting, driving it at the above speeds. The lathe is run alternately backwards and forwards a few times till the chaser has cut deep enough to guide itself. The belt of the screw-cutting gear is then cast off and the screw finished by hand. The expert Birmingham brass-fitter will no doubt laugh at this contraption; but it works beautifully, and there are no drunk threads after it.

Our first care after removing the rough exterior of the casting (an operation for which it is well to have a set of rough tools made of old files) will be to turn up the interior truly cylindrical and a nice easy fit for the object-glass. A slide-rest is the proper thing for this sort of job, but it can be done with care by means of hand tools, making plentiful use of the calipers. The flange against which the crown lens beds should be left wider than will be required, to be turned down afterwards. The outside is turned down next, leaving a flange at the point to which the cover-cap will reach when fitted.

Next the counter-cell may be turned up, leaving it just too large to enter. As this is a thin piece, it will be necessary to make a wooden chuck to hold it, and prevent distortion. A thick wooden ring, over which the brass ring fits loosely, will do. Split it at one side, put the brass ring on, slip the whole thing over the jaws of the scroll chuck, and expand the latter till tight. We can now turn up or screw the thin ring without fear of distorting it. A thread of 30 per inch is suitable for the counter-cell, and it should be an easy fit till very nearly home. The external thread by which the cell screws into the "end" should be a good deal coarser, 15 or 20 per inch. The "end" need not be anything but a plain cylinder, except for the internal thread at one end. The other end should be a fairly easy fit over the main telescope tube,

and while in position thereon should be drilled at three equidistant points, and screws fitted, each with a nut inside the tube. The holes in the tube should be broached out to a loose fit, or else a little longer than they are wide, to admit of a small amount of adjustment for squaring the object-glass (see Figure 12).

This is the usual plan in small telescopes. But it will save a lot of worry

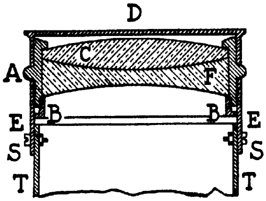


FIGURE 12

The usual form of cell for a small object-glass. A is the cell; BB the counter-cell; C the crown lens; F the flint lens; EE the end; TT the telescope tube, and SS the screws for attaching the end to the tube; D is the cover-cap.

afterwards if we have a cell provided with "pull-and-push" screws for squaring. A slight modification of the form of the castings for cell and end will be necessary for this (see Figure 11, II). And not only a modification, but a simplification. For the same pattern will serve for the castings for both cell and end, and if the cylindrical part be made deep enough to spare a ring

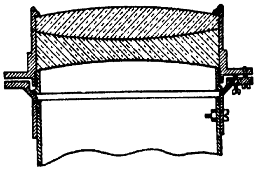


FIGURE 13

Push-and-pull screw cell. There are three equidistant pairs of screws, but one pair only is shown.

turned off for the counter-cell, one pattern of the form shown will do for the lot.

Figure 13 shows in section the form of the cell when completed. Great care is necessary in making the finishing cuts on the interior of the cell. It must be truly cylindrical, an easy fit for the lenses without pressure, and with just the merest suspicion of play between brass and glass. If overdone,

and too loose a fit, this may be remedied by inserting a strip of thin smooth paper as wide as the thickness of the object-glass between it and the cell. But this will not be necessary to a good workman. The counter-cell must not be screwed down tight, as strain of the glass will injure its performance very seriously. A slight rattle should always be heard when the cell is shaken.

The tube, which forms the body of the telescope, should be straight, strong and rigid. If these conditions be fulfilled, its actual material is of small importance, except for appearance. Brass is, of course, the proper material for a small refractor, and up to 3-inch diameter it will not be prohibitive in cost. But excellent tubes may be made of sheet iron, tinplate, wood, or even pasteboard. The suitability of the material will, of course, be partly determined by the size required. The writer on one occasion had an excellent tube made by a traveling tinker for a 3-inch object-glass. The man was so totally illiterate that feet and inches had no meaning to him. But being given a stick of the length of the required tube, and a strip of tin equal to its circumference, he made an excellent job.

The stops in the interior of a refractor tube may be turned out of wood. There are very often too many of these, and they are commonly made too small. One about half-way down the tube will be enough. It should fit tightly enough to stay where it is put, but not too tightly to be easily pushed up or down till the best position is found for it. It should not be only just large enough to pass the entire cone of rays from the object-glass; still less should it be so small as to cut down the aperture, as is too often the case. A good way of ascertaining whether the stops are too narrow is to put in a high-power eyepiece, point the wrong end of the telescope to the sky (or any bright object), and, looking through the object-glass, see if the tiny spot of light admitted by the eyepiece is visible from all parts of the object-glass, and right up to its edge. If not, the stops are cutting off some of the aperture, and should be removed, or shifted nearer the eye end.

To come to the eye end, the principal working part here is the rack-and-pinion focussing movement. This is a job which is hardly one for an amateur, and we would recommend purchasing it, as also the eyepieces, and for the same reason. They can be bought at a moderate price far better than the amateur brass-fitter could make them.

At least, three eyepieces should be obtained. If this number be decided on they should, for a refractor, be of about 2 inches, $\frac{3}{4}$ inch and $\frac{1}{4}$ inch, equivalent focus, respectively. If the telescope is of 4-inch aperture or more, four to six eyepieces will be found useful, and should range from $2\frac{1}{2}$ inches to $\frac{1}{6}$ inch equivalent focus to enable the objective to do itself justice on all classes of objects.

Part III.

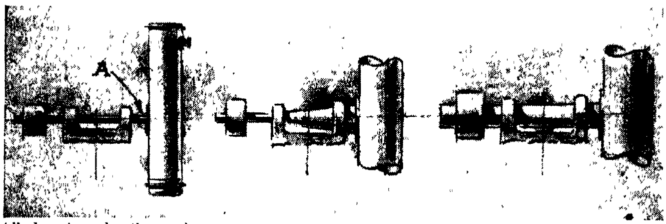
Fundamentals in the Design of Telescope Mountings; Rigidity

By Russell W. Porter
Associate in Optics, The California Institute of Technology

None of my chapters in the earlier parts of this book emphasized sufficiently the importance of *stability* in the mounting of the telescope—the absolute necessity of supporting the instrument in such a way that it will be free from vibrations—exasperating tremors and shimmyings that set the observer's star field fluttering when he no more than touches his eyepiece or when it is met by a summer zephyr. Often at first the amateur fails to realize that in the optical train of his telescope he has an optical lever, comparable in sensitiveness to the arm of a seismograph, a lever so highly compounded as to magnify a disturbance hundreds of times.

If we consider the conditions imposed on an equatorial support, and their bearing on rigidity, and for the moment disregard the stiffness inherent in the materials themselves—iron, steel, wood, aluminum, Bakelite and so on—and confine our investigation to shape taken by itself, that is, design, we shall find that the telescope's weight reaches old Mother Earth through two rotatable axles, declination and polar, the first of which rests on the second. The support of the "optick tube"—to quote Newton—falls naturally into two categories, outboard and inboard, so to speak; that is, the tube is carried either outside and north of the two polar axle bearings, or inside and between them. Similarly, within the former category there are two ways of handling the tube on its declination axle, either outside—the German type, page 24, Figure 23—which requires the added weight of a counterpoise, or between the bearings, as in the familiar fork.

First we take up the most familiar type of mounting, the offset, counterbalanced type—the German style—and right here I put my finger on a very common weak spot, the declination spindle itself, where it joins the tube. In the German form this spot lies at *A*, Figure 1, and it is a real "bottle-



All drawings by the author

FIGURE 1

At A, in the first sketch, is the Achilles' heel of the average home-made telescope: not enough cross-section. Second sketch suggests a remedy, tapering the axle. But this is seldom easy, so a practical solution is shown in third sketch.

neck." I have yet to see a mounting in which strength at this point has been overdone. If we make a schematic drawing of this part of the mounting we shall see at once that a jar at the eyepiece will produce there a flexure or bending and a consequent periodic vibration which is due mainly to a lack of sufficient cross-section at this point. Stiffness in the tube itself is usually quite well taken care of because of its relatively large cross-section.

In practice the amateur has to rely for his declination spindle on piping or pieces of shafting salvaged from junk yards. These are all cylinders, but it would be far better if cones were equally available (second sketch); and so the easiest way out seems to be to select a shaft or pipe having at least the diameter of the big end of the cone, as in the third sketch.

Still, it may be that the ingenuity of Young America may be able to dig up out of discarded motor car parts or elsewhere some gadget that has all the requirements of strength at *A*, without encumbering his mounting with useless metal at the counterweight end.

Now we come to the second member, the polar axle. Everything that has just been said of the declination member applies equally to the polar member, and even more so, since added weight and the handling of the declination

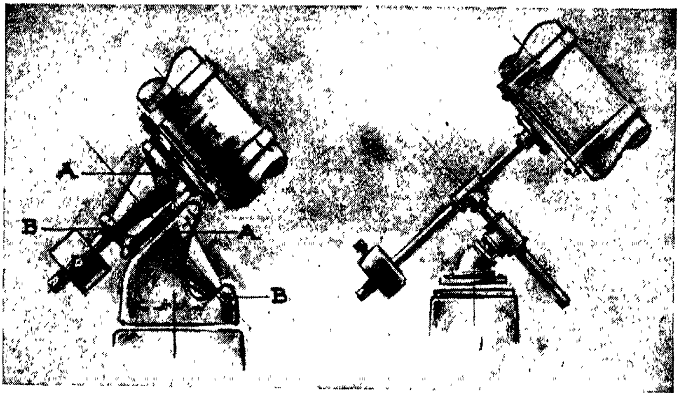


FIGURE 2

The first sketch shows a really solid form of counterbalanced equatorial mounting. Bearings A and A are the more important ones; B and B are less so. By contrast, note the second sketch, which is not an exaggeration of some mountings.

control increase the probability of vibrations. But here, at least, there is no excuse for a weak support. This member rests on the ground, and concrete is cheap.

An exaggerated form of mounting, having extreme rigidity for an equatorially supported telescope of the counterbalanced type, might take on the proportions of the first sketch of Figure 2, where the "outboard" bearings

A,A, of the axes are shown much greater than the other and less important ones *B,B*. A comparison of the first mounting sketched, with its companion, will make obvious what the writer is driving at.

But there are other ways of securing stability and still disregarding the kind of materials used. The precision with which an axis may be retained under rotation is controllable in two ways, either by a spindle *A*, turning in two well separated bearings *B,B*, as in the left-hand sketch of Figure 8, or

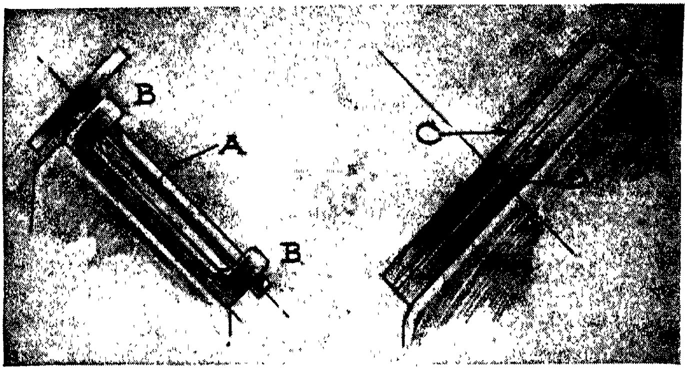


FIGURE 3

Two quite different ways of obtaining stable rotation: that is, in two separate bearings B, B, or else by a disk and track, with a central stud.

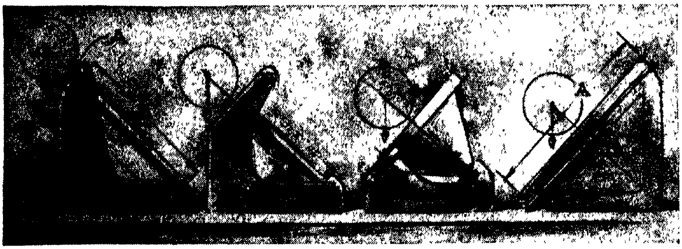


FIGURE 4

A progression by steps, from the first sketch of Figure 3 to the last sketch of the same figure—that is, from spindle to plate. The circles shown are for designating the position of the concentrated load of the overhung telescope tube. In the first and second steps the bearings are closed. The third shows the upper bearing no longer closed, but greatly expanded and open and resting on rollers. In the fourth the spindle or axle has disappeared and a circular or equatorial plate has taken its place. Note how the load moves inboard with each step.

a plate (or disk) C, centered by the stud D, and supported on the circular marginal track E of the right-hand sketch. Throughout all machine tool design we find these same two means of alining and maintaining axles in all sorts of combination, merging from one extreme (left) to the other (right) indicated schematically in Figure 4.

In all these progressions it will be observed that the sum of the two dimensions A and B remains nearly constant. If you skimp on either one, you sacrifice stability. In passing, Figure 4 represents the polar axis, but the principle described applies equally well to the declination axis.

Another interesting evolutionary sequence is the transformation of the straight fork into our old friend the "split ring."[1] In the four steps of

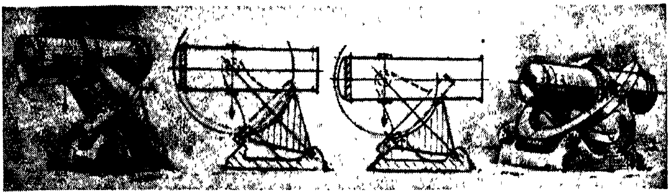


FIGURE 5

The evolution of the split ring equatorial mounting (fourth sketch) from the fork type mounting (first sketch). The second sketch is a projection of the first, and the third is a projection of the fourth. Here again the mounting, in its evolution, changes from outboard to inboard—note positions of the arrows.

Figure 5 the tube is horizontal and pointing directly south. The two middle sketches are shown in straight projection, and the first and last are thrown into perspective, for clarity.

Astronomers do not insist on reaching clear to the horizon. Atmospheric disturbances close to the earth render observations there almost worthless. When they desire observations on stars near the southern horizon they rely on those made in lower geographic latitudes. They set the limit of desirability somewhere around 15° altitude. This point is important to the telescope designer because it bears directly on the length of the fork arms. (We are considering here the non-counterweighted, symmetrical type, alone.) For, when the underside of the tube (Figure 5, first sketch) touches the upper ring bearing of the polar axis at A, the point B, at the intersection of the two axes of revolution above C, determines the length of the fork. The weight of the tube (and mirrors) concentrated at B is seen to overhang considerably the supports below, at X, Y and Z, and this does not make for stability.

To improve the unstable state of affairs (one of the main purposes of the split ring), the tube is seen in the series to be gradually entering the upper polar axis bearing, until it arrives at the position shown in the fourth sketch. However, in this transformation, the upper ring of the polar axis has been

[1] It has recently been called to my attention that the germ of the split ring can be traced back at least to the middle of the last century, when LaSalle either proposed the idea or actually incorporated it into one of his mountings.

severed, and a segment of it, at *D*, equal to the diameter of the tube, has been bodily removed. At the same time the fork itself has entirely disappeared.

As applied to large mountings, some engineers have criticized the "split ring" form as having introduced an element of weakness due to this splitting apart of the enlarged upper bearing of the polar axis spindle, on the ground that it forces removal of the equatorial plate or bulkhead *C* of the first sketch (Figure 5), which is so important in maintaining the circularity of the ring itself.

The weakness often found in the declination spindle, alluded to above, disappears in the fork type of mounting shown in Figure 6—or rather it is

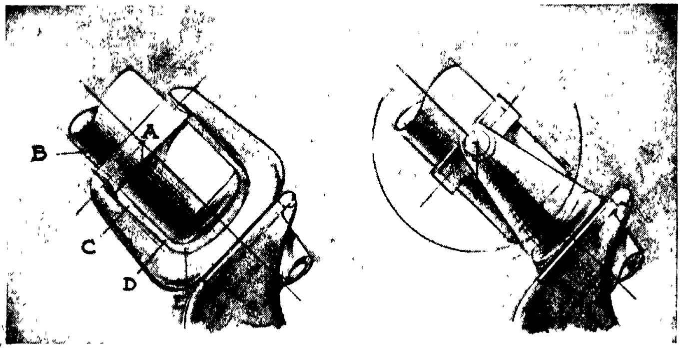


FIGURE 6

Although it will be of no practical application on the average amateur's telescope, it is interesting to visualize what happens to the tube in the two positions of the fork shown above, in the case of a large telescope. The great tube is adjusted as nearly as possible to coincide with the polar axis of the instrument but, due to bending caused by gravity, the fork will point below the pole of the heavens. Now, when the fork is in the position shown in the second sketch this can be corrected, simply by tilting the declination axis, but in the other position (first sketch) there is no corresponding remedy for flexure.

transferred to the forks themselves. The telescope weight, balanced and centered at *A*, tends of course to bend down the lower fork and pull down the upper. But the tines are locked together by a stiff ring *B*, which carries the telescope tube. This flexure is distributed between the two arms, and vibrations are thereby reduced. A useful point to remember in considering the design of the fork is that the equivalent cross-sections through it, at *C*, *D*, *E* and so on, should progressively increase, in order to avoid a "bottle-neck" effect at *E*.

Perhaps the leading paragraph of this chapter on telescope supports should have been a caution, a gentle reminder to the fellow who has devoted so many painstaking hours to perfecting his optical parts, that ordinary supporting systems as we know them in everyday life are not nearly sufficient

for his finished instrument. Our common supporting frames—chairs, tables, ladders, wagons, autos and so on—are designed and built to give a reasonable and durable strength, a "factor of safety." This standard does not at all suffice for telescope mountings—although there is the regrettable case of one enthusiast in Connecticut who so far violated the reasonable requirements of strength as to meet his death by being struck by his tube, which had parted from its declination spindle (that "bottle neck") while he was on the top rung of a step ladder. Far from requiring a merely moderate factor of safety, or even a high one, compared with ordinary standards of designing, the telescope mounting should contain much more mass and much greater cross-section areas in its design. I can conceive a mounting fabricated almost entirely out of good old concrete (Figures 7 and 8), with the two required motions—declination and right ascension—cast into the whole. Lightness is scarcely ever needed. The mirror cell and eyepiece alone need to be taken indoors, and I suppose that very few of the favorite six-inch instruments are transported or removed from the back yard. Plenty of weight (mass), correctly disposed, is one of the most effective and inexpensive ways of eliminating vibrations.

In Figure 7, which should be labeled "Porter's Folly"—so far as I know, as I write (1935), it has never been tried—is a design for a telescope mount-

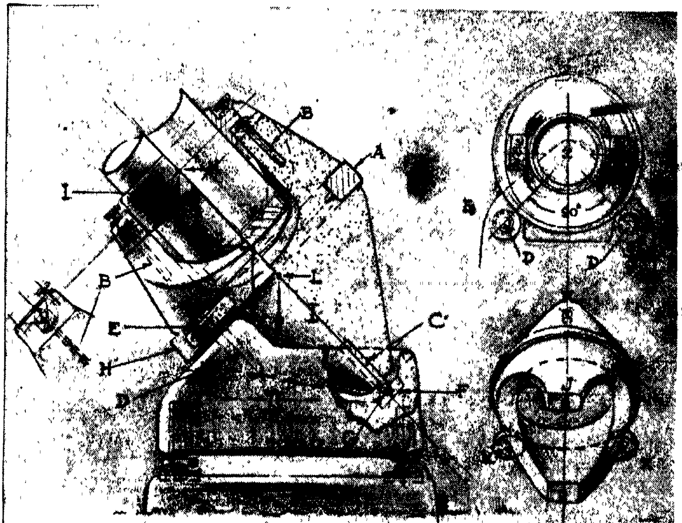


FIGURE 7

A mounting made of sand, cement and junk, with chief emphasis on massiveness.

ing which might prove to be the last word in stability, and I should sincerely like to see it tried out. It surely has the merit of cheapness, for it is mostly sand and cement. The prospective victim must first hie himself to the junk yard and unearth a discarded fly wheel, *A*, the bigger and heavier the better. The rim, however, should be in fair shape, and its machined edge not too badly pitted with rust, for on it the smoothness of operation will depend. With the proportions indicated, for a six-inch mirror tube, a fly wheel about 20 inches in diameter would be about right. Take a sledge and knock out the spokes and hub. The design must, of course, be all laid out on paper, in order that the maker may know how to set up his forms for the concrete. He must watch out to see that the forks are long enough to let the tube come down near the southern horizon without colliding with the rim of the fly wheel. The rest of the job is fairly obvious.

In concrete casting I, which can be poured with the wheel horizontal, two threaded studs, *B,B,* must be located, in order to permit later fastening of the declination bearings, and another, *C*, which positions the lower end of the polar axis. Casting II has two studs *D,D,* over which eventually will go the two large ball bearings *E,E,* (get these from a dismantled gasoline truck—main crankshaft bearings) and a small plate *F* to take the thrust from the steel ball *G*.

For adjustment in the meridian, casting II should be separate from the pier itself. The drive (hand) is most easily obtained by rotating the outer race of either one of the ball bearings with a smooth pinion *H*, and with just enough pressure to overcome the frictional resistance of the instrument. (Baily of Riverside, California, uses this drive on his 12-inch split ring, page 452, and it is entirely satisfactory.) Use ample reinforcing, of course—telephone wire, chicken wire, any old wire.

The sketch, as shown, is a meridian projection looking east, with both declination and polar axes in the meridian (plane of the paper). The telescope tube may be of the conventional pattern, and eventually will be balanced in ring *I*.

Finally, I should like to call attention to the location of the center of gravity, *J*, of all moving parts. The center of mass of the tube is, of course, at *K*, at the intersection of the two axes; that of the polar axis (casting I) somewhere near *L*. The final (resultant) center, *J*, will, if you look vertically down on the instrument, be found projected almost equally distant from the three supporting points *X,X,X*, of the polar axis (Figure 7, lower right-hand drawing), an ideal position for stability.

Setting circles should offer no special difficulties.

It will be noted that this freak mounting falls into the third progression of the series in Figure 4.

Who will be the lucky man to vindicate Porter's Folly?

Another concrete "folly" mounting is suggested, and is shown in Figure 8, but it requires an additional reflection, in order to obtain its fixed eyepiece, as in the Springfield type of mounting. The tube is cast rigidly to a large equatorial ring *A*, which might be another fly wheel, as in Figure 7,

but in this case it retains its hub and rotates in R.A. on a stud *B*, cast into the pedestal. The bearing here is on the under side of the fly wheel, on three ball bearings or rolls in the base. It might be even better to cast the wheel into the pedestal, and attach rolls to three studs set into the upper casting. Note that this design falls into the last step of the series in Figure 3.

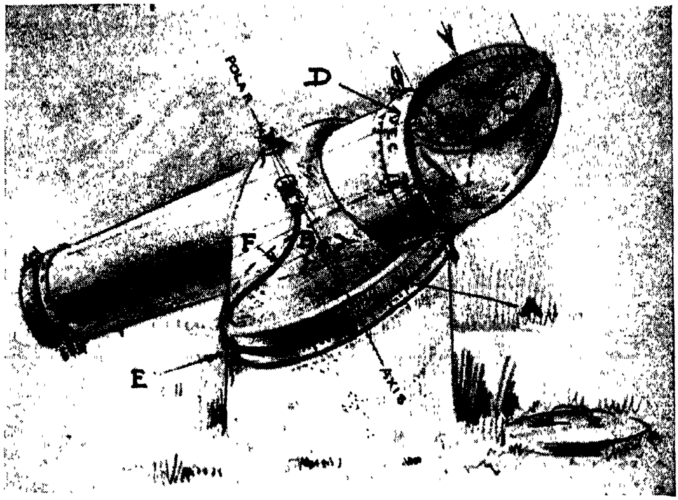


FIGURE 8
Another concrete mounting, rugged, attractive but with a serious drawback.

Declination is taken care of at the end of the tube by means of an auxiliary flat mirror *C*, placed at 45° with the axis of the concave mirror. This auxiliary mirror is rotated in declination around the ring *D*, at the end of the tube. Star following is with the pinion *E* and flexible shaft *F*. However, such an optical train as this is not to be especially recommended, on account of the introduction of a reflecting surface *outside* the concave mirror, where any departure from flatness is highly detrimental to definition.

A good, serviceable polar axle (Figure 9) can be made from a piece of 6-inch pipe some two feet long, on one end of which is screwed a standard pipe flange, the other being closed by means of a cap. Any jobbing machine shop will, in an hour or two, fasten the flange to the face plate of a lathe, turn up the edge, screw in the pipe and cap unit, and drill out and press in the stud *A*. With this done, the amateur can pretty well get along by himself. On his concrete pier *B* he must fasten the plate *C*, which carries the studs for two ball bearings. On these bearings will rest the edge of the

flange. At the other end he will arrange a plate *D* to take the thrust of the polar axis. Then, on the broad machined face of the flange, he can fasten either the declination bearings for an offset, counterpoised tube *E*, or a fork *F*. Both are indicated lightly in the drawing.

An alternative, and perhaps a better one, by which the machine shop

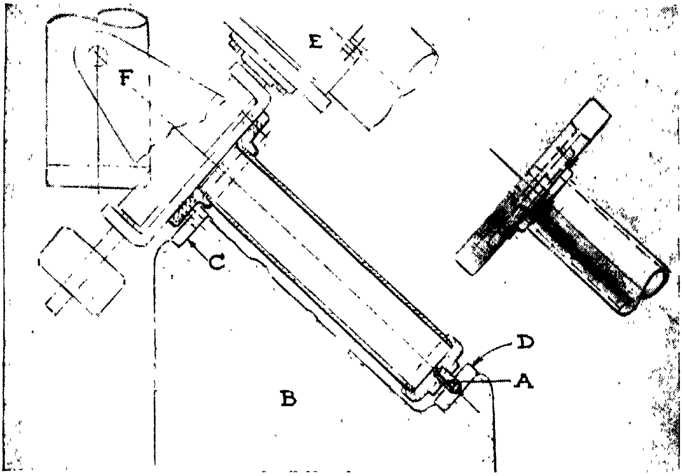


FIGURE 9
A serviceable, sturdy polar axle, made of 6-inch pipe.

may be eliminated, is indicated at the right in the same figure. Here a fly wheel is shown bolted to the flange of the axis already described. It not only gives a larger surface to attach the tube supports, but the increased diameter distributes to better advantage its three-point geometrical support; that is, the two ball bearing rolls and the end thrust. The axis has now entered class three of the steps shown in Figure 4.

Up to this point we have in general considered the telescope as an outboard affair, fastened to the upper end of the polar axis spindle and overhanging the spindle's upper bearing. But this need not necessarily be, for if we wish, we may support the telescope between the two bearings, and in a way this arrangement makes for stability.

There are several well-known mountings designed on this principle, the most famous being the 100-inch Hooker telescope at Mt. Wilson. Unfortunately, part of the northern heavens are inaccessible to it, and everyone knows it is human nature to itch to explore a region where one has been denied access. The device is called the double yoke, and is shown on page

26. The upper end of the tube collides with the yoke near the upper bearing, at about North Declination 64° (in the 100-inch) and is deprived of all declinations from there to the pole. The yoke is sometimes made a little longer than the telescope, and then the instrument becomes almost universal. One way of getting around this drawback of the double yoke is to draw on a property of the split ring, as shown in Figure 10, first sketch. Then the telescope nestles down into the split ring itself and is looking squarely at Polaris. Another way is shown in the second sketch. It comprises a stout

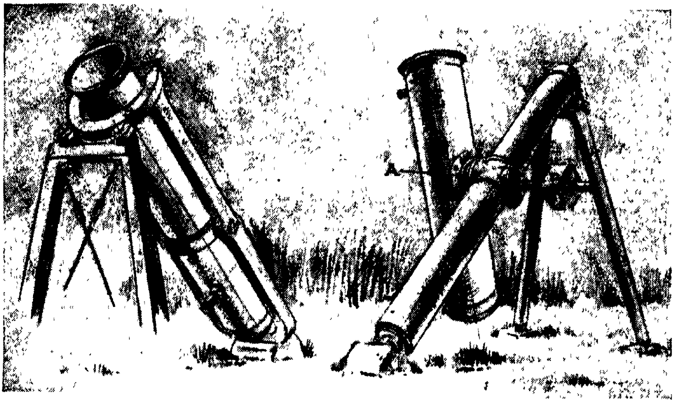


FIGURE 10

Two ways to gain access to the circumpolar region, yet not sacrifice the rigidity conferred by the inboard type of mounting. Attractive mountings.

pipe 4 to 6 inches in diameter, in two parts, threaded into the pipe cross. Screw the end plugs into the pipes, and attach studs for pivots. Fasten the telescope tube to a threaded plug that turns in one of the lateral tappings, as at *A*. Add counterweight *B*.

If the telescope is permanently located it may benefit by having the pipes filled with concrete, giving it greater mass.

There is an objection to using pipe threads, as is sometimes done, for the rotating bearings in a telescope mounting—they are tapered, and so if they fit snugly in one position they will be loose in another. To overcome this defect, the threads should be recut on a lathe, or else bored out and rebushed.

The only vital part of this mounting that requires to be kept slushed with hard grease is the thread that controls the declination axis, and to its credit, the whole affair stands on the good old three-point geometrical support.

Byron Graves suggests that it is probably easier for the fellow whose tool equipment is confined to a saw and hammer to build up his polar axis out of wooden two-by-fours, choosing the double yoke (see illustration, page

315), and to let his tube swing freely within it. The whole rig is collapsible and well suited for transportation in a car, and is easy to set up and adjust. I recall particularly one of these mountings, that shows up annually at Stellafane, from Pittsfield, Mass., sponsored by our "HCF" member, Everest.

The Tube: Bakelite and composition tubing, reinforced with rings, makes excellent tubes for keeping the optical parts "put"—fixed in relation to each other. Wood is to be recommended. Lattice tubes are all right, if one has the patience to make them, but a simple cylinder of sheet metal, adequately ventilated in order to avoid temperature effects that impair good seeing, is by far the easiest to make, and probably the stiffest. T. B. Trott, of England, claims superior results—steadier seeing—from an exterior covering and interior lining of sheet cork, as applied to a metal tube. The lining is a series of pieces 12 inches wide and just too long for the interior circumference, so that they can be butted and snapped in under pressure. The exterior covering is cemented on. Generally speaking, an excess of weight in the tube is a good thing. Do not forget those tiny but disturbing vibrations so easily set up in light material, on the slightest provocation. So my choice for tubing is a generous thickness in metal. I should like to be able to give a telescope tube a good violent blow with my fist and not see the star I'm looking at disappear from the field of view.

The Mirror Cell: With small mirrors this should have a three-point support at the back, and another around the edge. These points should be covered with materials that have a little "give" to them, so as to allow for expansion—paper, blotting paper, wafers of wood, cork from auto gaskets—and not set up so tight that a slight shake cannot be detected. Safety guards over the front edge should not quite touch the face of the mirror.

Collimation (lining up) of the mirror axis with that of the tube may be

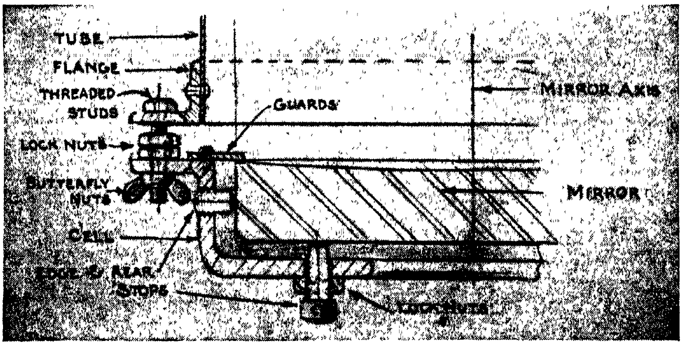


FIGURE 11

A design for a mirror cell. Threaded studs, guards and edge and rear stops, are all spaced 120° apart. It is possible to make many variations on this design.

taken care of where the mirror cell is attached to the tube, at three stops 120° apart. One way of doing all this is shown in Figure 11. There are countless others—as many, almost, as there are telescope makers—but the same requirements hold in all. Note that the glass is well ventilated, and the cell easily detached from the tube without disturbing the collimation. The brake drums of automobile wheels make very good mirror cells. They can be found in auto grave yards, in sizes to suit almost any diameter of mirror, and the drums are thick enough to permit threading for the supporting screws. Flange brackets for attaching to the tube may be either welded or bolted on.

At the other end of the tube are the diagonal and ocular. Hack saw blades make good thin "knife-edges" to support the diagonal. The assembly is shown on page 20, Figure 19.

If one has access to a lathe he can increase the comfort of observing by adding an additional ring to the telescope tube, and thus revolve his eye-piece and prism (or flat) to any desired observing angle. This is shown in Figure 12. My good friend James Barkelew has suggested an arrangement

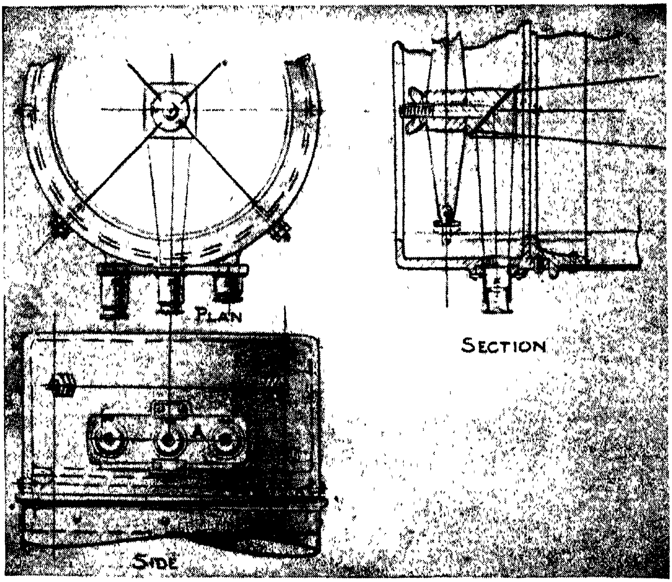


FIGURE 12

Left: Barkelew's battery, plan and side and sectional views.

or extra refinement in which there is a battery of eyepieces on a single slide, as at *A*, bottom, same figure, so that one power can be compared quickly with another, without having to refocus. Who cannot recall asking for a higher powered ocular, while the other fellow fumbled around in the dark and finally located it on the pedestal or in his pocket, or perhaps in the grass. Rotating the eyepiece and diagonal, however, is of course a common practice. It is open to question whether the rotation of the eyepiece is not better handled by turning the tube as a whole, in a ring carrying the declination studs, rather than by a ring or collar at the end of the tube, as just described. The movement of the tube as a whole does not affect the alinement of the optical elements it contains.

Of all the available sources of a stable polar axis I know of nothing better at the present writing than the crankshaft of an automobile engine,

FIGURE 13

An old engine ignominiously spends the rest of its life upside down.

together with the engine block itself, for bearings and support, and the bigger the engine the better (Figure 13). This assertion will probably jar the sensibilities of many who love to see a graceful design in a telescope ensemble; for frankly an old, inverted gasoline engine block, turned end for end, with one end tipped up in the air, is anything but beautiful. However, we are faced with two conditions: the limitations of the amateur's pocketbook, and the requirement of extreme rigidity in his mounting—assuming that he desires to exhaust all the possibilities of his beloved mirror. Throughout

this chapter on mountings the writer finds himself continually between two groups of amateurs. One, relatively small, with ample machining facilities of their own, and all the resources of the pattern shop and foundry, the other that far greater number who have made equally good mirrors but who, from the limitations of their pocketbook or from some other circumstance, are denied the advantages enjoyed by their more fortunate fellows. Frankly, my sympathies are with this latter class, and they surely compel one's admiration by the ingenious gadgets they have evolved in overcoming their mounting problems. To which class should we cater?

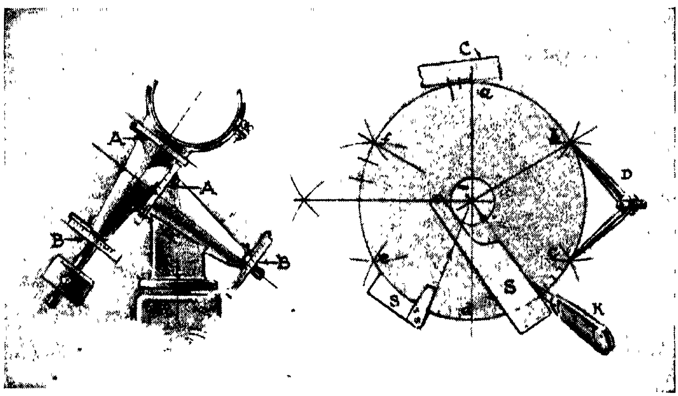


FIGURE 14

Left: Another mounting, conventional in type. Right: Laying out the setting circles. If these are made by hand, make sure that, whatever style of straight-edge, S or S, is used to guide the scratcher, the line will radiate from the center of the circle and not the edge of the shaft. Single degrees may be transferred from a little scale prepared in advance, which may be straight (good enough), as at C, at top of the drawing. If laid out as shown, there will be no accumulated errors, as errors are distributed round the circle.

On the conventional counterbalanced mounting shown in Figure 14, left, setting circles are located either at *A,A*, or at *B,B*. They are usually attached to the axes themselves, with the indexes fixed to the axis bearings. The locations at *B,B* are rather more favorable for night reading, as they are well out in the open, with plenty of room around them for the flashlight and the visor of one's cap. If machined seats for centering them are not available, the tyro must "cut and try" when fastening them, until excentricity has been eliminated. Above all, let the circles be as large as possible and the graduations coarse—single degrees for declinations and their equivalent (four-minute) intervals on the hour circle. If a dividing engine or lathe is not available, the graduations will be quite good enough if laid off on the

drawing board with a compass. It may be too obvious to describe, but one procedure is shown in Figure 14, right, where the dividers, after swinging the circle, mark off the major divisions *A, B, C,* and so on, 60° each. Next adjust the compass by cut and try until the 10° intervals are found, and, finally, subdivide the single degrees. Brass makes good circles. Scratch the divisions deeply.

No verniers are needed; the field of a low-powered eyepiece will almost take in the moon (half a degree) and one should surely be able to set his

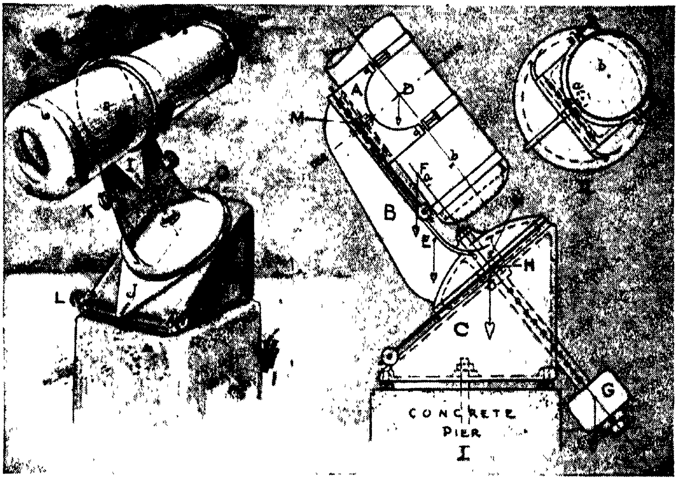


FIGURE 15

index to a quarter of a degree with sufficient accuracy. If the object he is looking for is not there in the field he may look elsewhere for the trouble and not in the accuracy of his setting circle.

A one-legged mount—for the fellow who wants a solid support, is able to make his own patterns, and hasn't the means to pay for expensive machining —is shown in Figure 15, which is almost self-explanatory. This form of mounting is so designed as to bring the center of mass of all rotating parts to *H,* the ideal place for smooth following in R.A. It is accomplished as follows. The weight of the tube is centered at *D,* that of casting *B* is at about *E:* their combined weight is at *F,* and counterweight *G* brings it down the axis to *H,* into the equatorial plane where the drive in R.A. is applied. The instrument is now in complete equilibrium and should prove very stable. The diagram marked II is a view down the polar axis and shows the tube and leg of *B* offset on opposite sides of this axis.

Slow motions are produced (as in the Springfield mounting) by the insertion of steel sheets *I* and *J* (at the left) to avoid costly worm gearing, but the leverage has been increased by lengthening their spurs so as to make the slow motions more sensitive. The slow motion screws *K* and *L* are threaded at one end. The leg of casting *B* need be only long enough to permit the telescope's reaching the southern horizon before striking casting *B* at *O*.

Machining.—The bosses forming the bearing surfaces of the declination and R.A. plates which define their axes, may be swept across a Carborundum paper wheel (every foundry has one in its snagging room) or they can be filed and scraped flat by hand. The holes for the studs *M* and *N*

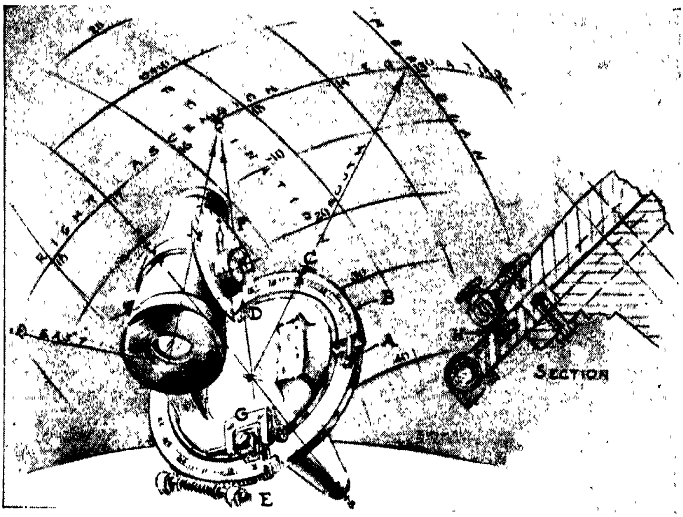


FIGURE 16

A slip ring on the R.A. circle will save a lot of added bother.

are simple drill press jobs. The studs should be equipped with spring washers and lock nuts to provide adequate friction between the plates. I cannot see where there is five dollars' worth of paid labor in the whole affair.

Figure 16 has been drawn to show the convenience of having a divided hour circle on the polar axle, *always* indicating local sidereal time. With this in mind I have tied it up, in the drawing, with a background representing the astronomer's framework of the heavens, to which he refers all celestial objects. It will first be noted that the 13-hour circle of R.A. happens to be on the meridian (we are looking toward the southeast heavens). This of course means that the right ascension of the meridian contains the index *C*

(affixed to the earth), and that the hour circle slip ring *A* has been so turned that division 13 is directly under the index. This circle rides in a groove cut in the worm wheel *B*, that is being continually driven by the clock or motor at *E*, and always indicates the right ascensions of the stars and keeps step with them, no matter where in the heavens they may be.

It should also be noticed that the worm wheel itself is a slip ring, (see section, same figure) within which, and on which, the polar axis rests. This is found necessary since, in order to keep the clock and hour circle going continuously throughout the evening, provision must be made for swinging the tube to bear on objects in different parts of the sky, and then to adjust the tube back and forth by hand until the object is brought to a satisfactory position in the center of the field. This arrangement necessitates an additional index *D*, on the polar axle itself. As shown in the illustration, the telescope is "gunning" a star on the celestial equator (zero declination) at R.A. about 15½ hours. See how easily the setting is made. Turn the 'scope until index *D* is opposite 15 hours 30 minutes on the hour circle, and to zero on the declination circle *F*—and there you are.

With an hour circle of this kind keeping track of star time is unnecessary, for the clock-driven circle *is* the equivalent of a watch running on star time. To get it going, the procedure is to bring any bright known star into the center of the telescope field and set the circle to that star's R.A. (taken from the Ephemeris), using, of course, index *D*.

As an extra refinement for setting an object carefully in the center of the field, without disturbing the hour circle, a tangent screw may be added to the polar axle at *G*, the screw bearing against a stud *H*, that can be clamped to the worm wheel whenever fine setting in R.A. is desired.

It will be rather difficult for the amateur to install these controls on his mounting unless he has access to a lathe. Offhand, I can think of no analogous parts that he might retrieve from the junk yards and adapt to his needs; yet the uncanny way that amateur telescope makers dig out perfectly efficient dudads from the disemboweled parts of abandoned automobiles is truly remarkable.

Résumé: First of all, then, *stability*. Secure the requisite rigidity by well-chosen spindles of generous cross-section where needed. Give the entire mounting—tube, spindles, bearings—plenty of mass (weight). If you attain these elements, don't worry about how regular the thing looks—don't be hidebound by precedent.—*Pasadena, California, March, 1935.*

[EDITOR'S NOTE: A method of insulating metal tubes which was briefly mentioned in the foregoing discussion was described in detail in an article in the *Journal of the British Astronomical Association*, Nov., 1934, and that article is reprinted on the following pages. Beginners need not worry much about temperature effects in telescope tubes, but critical old observers, trained to see fine detail, usually do not ignore them. Wooden tubes also serve, many think, to give fewer temperature troubles—but such tubes may sag. Atmospheric "boiling" is often right in the telescope itself.]

Cork Insulation for Reflecting Telescopes

By T. B. Trott

I have found that temperature effects in iron-tubed reflectors can be very much reduced by covering the interior and exterior surfaces with a layer of agglomerated cork sheeting from 1/8 to 1/4 inch in thickness. It seems likely that most, if not practically all, of the residual effects still visible in a cork-insulated tube are not really "tube currents" at all, but mirror currents —convection currents set up at the silvered surface of the mirror. Practical experiment has convinced me how very formidable these latter disturbances can be at times. A mirror with a temperature only a very few degrees higher than that of the surrounding air will produce a whirling mass of convection currents which no amount of forced draught will disperse.

Sheet cork varies a good deal in quality. The best has a soft and elastic feel about it, and is easily compressed between the finger and thumb. It is composed of cork granules of appreciable size. Apart from its superlative insulating qualities, cork sheeting is very convenient to use. It can be cut with an ordinary pair of scissors, and will do everything required of it in a most obliging manner.

The aperture of my telescope is 9¾ inches, and its focal length 99 inches. It is used in the open air. The tube is 100 inches in length and has a diameter of 11¼ inches. It was fitted with an internal layer of cork, neatly and efficiently, in a little over one hour. Strangely enough, it is much more difficult to apply the outside layer, and it takes a much longer time to complete.

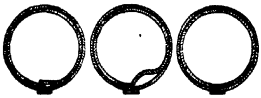
A cork-insulated tube must be ventilated. If this is not done a peculiar effect will be produced, very similar to that seen when a mirror, or object glass, is not properly squared on. This is probably due to delayed radiation of heat from the air within the tube, and was foreseen and pointed out by Dr. W. H. Steavenson in a letter to me some time ago. I am indebted to him for much help and valuable information.

The inner layer of cork was fitted in sections of 12 inches, not overlapped, but placed end to end, so that a smooth, even surface was obtained throughout the whole length of the tube. The illustrations (which are not to scale) should make the method clear. No adhesives are necessary, the secret being to cut the sheeting so that its length is a little greater than the circumference of the tube. I found about ½ inch to be correct in my particular case. Larger tubes would require more overlap. The size of the sheets used was 36 by 12 inches. If the circumference of a tube is greater than 36 inches, the sheeting can be inserted in two or more pieces in precisely the same manner as described, and it will "stay put." The inner surface of the tube was given a coat of "dead black."

In my own particular case I find that adequate ventilation can be obtained by cutting circular holes about 3½ inches in diameter, and situated at intervals of 24 inches along the whole length of the top part of the tube,

from mirror end to open end. The first hole should be 24 inches from the mirror. In addition, a similar hole is cut 24 inches from the mirror, and at the underpart of the tube. In my opinion it is inadvisable to add more holes along the underpart of the tube, as they would probably introduce convection currents from the heavy iron mounting of the telescope.

The method of applying the outside layer of cork can, I think, be left to individual discretion, but my way can be seen from the illustrations. The



sections are secured by a strip of cork 3 inches wide, running the whole length of the underpart of the tube, and held in position by liquid glue. It was applied in sections, the strip being held in position by twine wound round and round the tube, spiral fashion. When the glue is dry the twine can be removed.

I have gone to the length of covering the finder, and even the rack mount, with an external layer of cork. This may be carrying precautions unnecessarily far, but I mistrust such masses of metal so near the open end of the tube. They have a high specific heat value. We must not forget that, in convection currents, we are dealing with something very delicate and intangible. I find, for example, that I can get rid of a good deal of bad seeing simply by putting on a thick overcoat. The coat prevents heated currents of air from the human body surging across the open end of the tube. These disturbances are probably often mistaken for tube currents, and are quite serious while they last. Fortunately, however, they are not continuously present, but get wafted across the field of view at more or less frequent intervals—especially on still nights. When the coat warms up the trouble re-appears. I obtain far better seeing with my insulated tube than I ever did before the insulation was applied. There is no doubt whatever about that.

I conclude with a note of caution. Reflecting telescopes are notoriously fickle and capricious, and although I believe that cork insulation will be found advantageous in most instances, it is by no means certain that this will be so in every case. To any intending experimenter I would therefore suggest that he minimize his trouble and expense by applying the inner layer first. This should result in a marked diminution of temperature effects. Should no improvement be apparent, it would be useless to go any further in the matter. On no account apply the outer layer first.

Part IV.

The HCF Lap

By A. W. Everest

HCF is Uncle Ephram's abbreviation for honeycomb foundation, a material universally used by beekeepers to encourage the bees to build their combs straight in the hives. For the polishing lap, it should be the pure beeswax variety, unwired, sold by dealers in beekeeping supplies under the trade name "Medium Brood Foundation." This material runs seven or eight 8 by 17 inch sheets per pound and costs about $1.00 for that amount. It is also available in the "Jumbo" size, 2 inches wider than the above.

HCF is made by running thin sheets of beeswax through embossing rolls which fill it with small tetrahedral depressions called "cells," and it is the delicate walls between adjacent cells that form the facets of the lap. The stroke of the mirror causes a whirlpool action of the rouge and water mixture in the cells, agitating the rouge particles upward, so that they wedge against the edges of the facets in the direction of the stroke. When the stroke is reversed, these particles break away and are replaced by others on the opposite sides of the cells—and so on, back and forth. Apparently it is these tight wedges of rouge that do most of the work, practically no rouge becoming embedded in the surface of the wax facets.

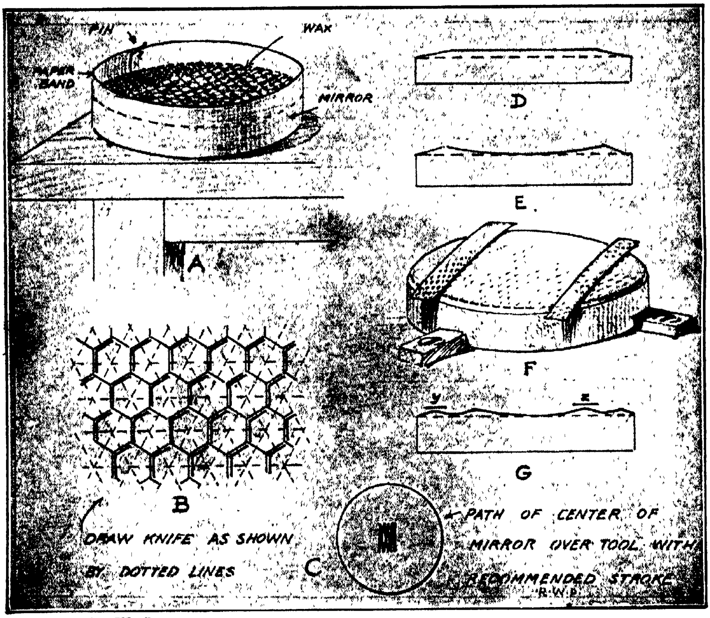
The advantages of HCF are: comparative freedom from scratching, sleeks and fog; retention of rouge charge for long spells of polishing; ease of making laps, either full size or special shapes for zonal correction; and speed of polishing—although the latter is not so noticeable with the new Pyrex disks now in general use. On these, harder pitch tools and more pressure may be used. The main drawback attached to HCF is the inferior optical polish produced. Its action is so drastic that the marks of facets show plainly under the knife-edge test. For small optical surfaces, this tendency can be reduced to a satisfactory extent by tapering off with fine washed rouge and reduced pressure. But on larger work, enough of this uneven surface texture will generally remain to be injurious to fine star images reflected from an otherwise perfect surface. Therefore, HCF can be recommended only as a medium for bringing the surface to a complete polish and reducing zonal irregularities that may be found at the end of this operation. From then on it becomes, at the most, an accessory of the pitch lap.

Various methods of using HCF will suggest themselves to the mirror maker, a suggested routine being as follows.

For the full-sized lap, warm the glass tool to about 110°F, dry it thoroughly and lay it, face up, on the work bench. Pour on pitch hot enough to spread out evenly to a thickness of not over 1/16 inch and to hold the HCF to the tool. While the pitch is still warm, lay on a sheet of HCF. Wet the mirror with soapy water and press the HCF through the pitch, right down to the surface of the glass. Trim off the surplus HCF around the edge, and the lap is made.

This produces a lap which does not yield to cold pressing, and contact is to be obtained and retained through the tendency of the facets to wear slowly away. If the pitch is accidentally applied too thick the lap may still be used, but it must be channeled similar to the pitch lap. Otherwise it will polish irregularly, mostly at the center, since the pitch in the center has no place to flow.

Use soap water for the rouge mixture. To get the proper degree of soapiness, splash a bar of soap around in a pan of water until a sample of



Drawn by R. W. Porter

METHODS OF USING HCF

HCF immersed in it for a moment will retain a film when removed. The function of the soap is to make the mixture stay on the lap and flow in the proper manner. In the chapter which this one replaces, in earlier editions of this work, the worker was advised to draw a blunt knife through each row of facets in all three directions, as shown at *B*, but this is unnecessary when using soap.

To get contact, dip the mirror into the soap water, hold it on edge for a moment, to allow the surplus to run off, and then dust on as much rouge as will stick. This will produce a grinding action when applied to the lap and, since wax is softer than glass, the lap will receive the grinding. Use short, straight strokes, as shown at *C*, for a few moments or until you can see, upon removing the mirror, that every facet on the lap has been touched, indicating complete and uniform contact. As a further refinement, rub a wet cake of soap lightly over the surface of the lap, wet the mirror and then use the same strokes to work up a good suds. At this point the facets can be seen and the condition of contact determined by looking through the mirror.

For polishing, use a thin rouge mixture. A heaping teaspoonful of rouge in half a glass of soap water is about right. With this thin mixture there is a pronounced drag, that is, the friction between mirror and lap requires considerable muscular effort to overcome. The facets are visible through the mirror, and the hair-line wedges of rouge on the working sides of the facets can be seen as they form and break away. This is the condition necessary for rapid polishing.

After the first few minutes of work, wipe up the mirror to see whether the polish is coming up evenly. If either the center or the edge starts to polish first, a wide departure from a spherical surface will result. Any such tendency must be corrected at the start by further "grinding" of the lap, as noted two paragraphs above. As a rule, the HCF tool with solid backing, as recommended, will start polishing slightly faster at the edge than at the center, but as long as some polish can be seen all over, this may be ignored, since the lap will then soon straighten out of its own accord.

After replacing the mirror on the lap, following an inspection, the rate of polishing may prove to be reduced, due to the rouge having settled in the bottom of the cells. This should be agitated back into suspension with a camel's hair brush. Slight additions of rouge with an eye-dropper at five-minute intervals will also help; or maybe just water to keep the cells full, thus "building up" gradually to the correct dilution for maximum drag. This may be done by sliding the mirror nearly halfway off the tool, adding rouge to the exposed area, and then repeating the procedure for the other side.

After an hour's polishing, the rouge mixture will become more or less contaminated with ground wax and glass, losing some of its drag and acting more and more like a lubricant. When this becomes very noticeable the tool should be flushed off and recharged with fresh material.

As an indication of what to expect, a properly ground Pyrex disk, say 10 inches in diameter, should be brought to a complete polish in about five hours, and should prove to be very nearly spherical if stroke *C* of the illustration has been used throughout.

Caution: Be careful when removing or replacing the mirror. A single slip may result in shaving off an area of the facets, which will not come back to contact until the rest of the surface wears down. Do not leave the mirror on the lap from one day to the next, as a protection against dust, for beeswax contains a trace of acid put there as a preservative by the bees themselves,

and after a prolonged period of contact this acid will attack the glass, leaving an imprint of the honeycomb pattern which can be seen both visually and under the knife-edge test.

For zonal correction, strips, arcs or special shapes of HCF are used on a lap especially prepared to hold them, since it would be unsafe to lay these on the good lap. To make this, lay a sheet of HCF, trimmed to size, on the face of the mirror. Wrap a paper band around, as shown at *A,* and pour in plaster of Paris to a depth of about one-sixth the diameter of the lap. As the plaster sets, press it down with the hands, to insure contact; and before it is too hard, level off by scraping across in several directions with a straight-edge.

The HCF strips for zonal correction, as at *F,* are cut to shape with shears and dipped in soap water, laid on the special lap where required, slightly crushed into contact with the mirror, and then given a rouge charge from

THE DISCOVERER OF THE HCF LAP
From a pencil sketch by R. W. Porter.

the eye-dropper. Strokes should be very short, and the mirror should be rotated slowly but uniformly for one or more *complete* revolutions. Test often, as the action is fast. Ten revolutions should be about the limit per spell.

As a typical example of zonal correction, suppose we had the turned-down edge shown in apparent section at *D.* It would require the removal of a considerable amount of glass to wear the mirror down to the level shown by the dotted line. But by drawing the knife-edge back slightly to get the appearance shown at *E,* the material to be removed will be found located mostly in one zone. At this position the center appears to have the same

depth as the edge. A similar setting of the knife-edge should be selected for all zonal irregularities when any sign of turned edge is present—that is, the depressed zones should be made to appear at the same level as the edge of the mirror.

Returning to the example of correction, the problem is to remove the material above the dotted line. Strips of HCF may be laid on the lap, as shown at *F*, to wear down the crest, although arcs would be somewhat better for bringing the action where it is wanted. Strokes parallel to the strips will concentrate the action to about the width of the strips, while strokes at right angles will ease off the effect. This will give something like *G*. The next step is to peel off the strips and relocate them, one just inside and the other just outside the first position, to remove the new crests formed by the previous operation. These maneuvers are continued until the surface appears practically flat, when a final blending should be given on a pitch lap of the conventional type.

Sometimes it is necessary to make a correction in some area where it is awkward to balance the mirror on the small strips required. Take, for example, a bump at the center, or a raised zone very near the center. In such cases a useful stratagem is to add near the edge of the lap three small balancers of HCF which have been dipped in soap water but no rouge applied. The mirror slides on them easily, and in perfect balance, but no polishing takes place.

For accurate location of zones when the mirror is on the testing stand, drive in a row of pins at half-inch intervals along a straight piece of wood a quarter inch or so square and about two inches longer than the diameter of the mirror. Hang this across the horizontal diameter of the mirror, with a supporting loop or semi-circle of wire up around the upper half. When the mirror is wholly illuminated, the pins look black, though when the knife-edge shadows appear they become brilliantly illuminated by diffraction. In other words, they are easily seen at all times.

When measuring zones, measure them on both sides of the mirror. The shadows travel over the crests of the zones in much the same manner as shadows 1 and 3 of the true paraboloidal figure, as explained in "A Study in Shadows" (Part X, Chapter VII), and an inspection at both sides is advisable in order to make sure of the location of the highest point.

For the final blending on the pitch lap, use short strokes and stop to press often, the idea being to keep the surface of the lap complementary to the surface of the mirror and then to make the high spots on the one ride the high spots of the other.

The method of parabolizing on the full-sized pitch lap is covered elsewhere in the book. If trouble is experienced when changing from spheroid to paraboloid in a uniform manner with the strokes recommended, careful use of the HCF strips before each spell on the pitch lap will help to remove the surplus material.

Part V.

A Motor Drive for the Telescope

By John M. Pierce

A telescope, when mounted equatorially, according to popular belief allows us to follow the stars in their courses across the heavens by turning the polar axis of the mounting at a uniform rate of speed, one turn in a sidereal day of 23 hours, 56 minutes, 4.091 seconds, or about 86,164 seconds, civil time.

When a mechanical drive is attached which rotates the telescope in this manner and at this speed, we can set it to observe a star or planet, start the driving mechanism, and observe the heavenly object for hours, if we wish, without further attention to the movement of star or instrument. Should we try, however, to take a long-exposure photograph through the same telescope we would find that, instead of a good, sharp image, we would get a blurred or oblong image, showing that the instrument did not follow accurately. Too limber a mounting, with sagging or vibration, also irregular refraction (the cause of star twinkling) may combine to produce this result.

Another cause of difficulty in our plans for making a simple driving mechanism is the regular refraction caused by a star's light entering our atmosphere at an angle. Even while a star is still below the horizon this causes it to be visible, as shown in Figure 1, and all stars except those directly overhead appear displaced by varying amounts, all appearing to be nearer the zenith than they actually are. As this displacement varies by geometrical ratio, from over one-half degree at the horizon to zero at the zenith, its effect is to give the star a varying *apparent* rate of motion as it crosses the sky. This rate will always be somewhat slower than its actual rate of speed, except at the time when it crosses the prime meridian, where it will reach its normal rate of progress.

This also causes a star to occupy a fictitious position in the sky, its actual and its apparent right ascension coinciding only when it is in the meridian, and its actual and apparent declination only at the zenith. The paths of the stars are not accurately arcs of circles, centered on the celestial pole, since stars at different declinations will be lifted up by different amounts, thus giving a multitude of different "poles"; even the celestial pole itself will appear in a fictitious place, for the same reason.

Thus driving a telescope so that it will accurately follow a star is a tremendously complicated problem and is only solvable in part. The late Professor King of Harvard worked out a plan for setting the polar axis of the telescope on a fictitious pole, which enabled him to secure excellent photographs of several hours' duration without manual following or adjustment. Of course, he had to reset his polar axis for stars in different parts of the sky. The Hurlbut-McMath Observatory uses variable speed motors to drive both R.A. and Declination axis on their instruments. With these, excellent motion pictures of the moon, Jupiter, sun-spots, etc., have been taken.

These expedients are, however, away beyond the resources of most amateurs, and we had best use a stationary polar axis and a constant speed

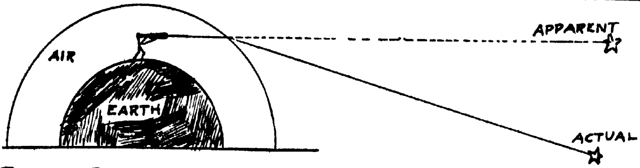


FIG. 1. REFRACTION BY THE EARTH'S ATMOSPHERE.

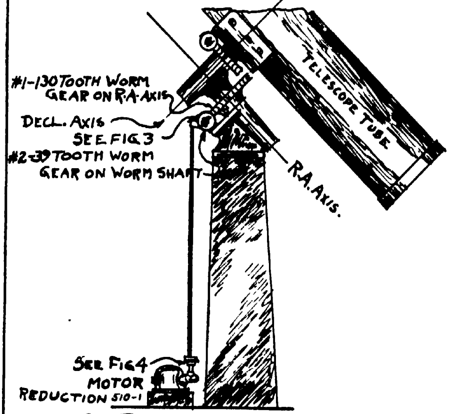


FIG. 2. DIAGRAM OF GEAR TRAIN.

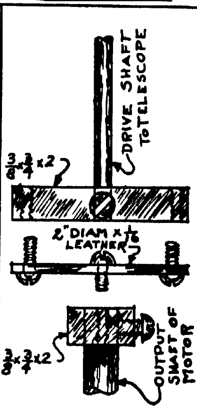


FIG 4 FLEXIBLE DRIVE

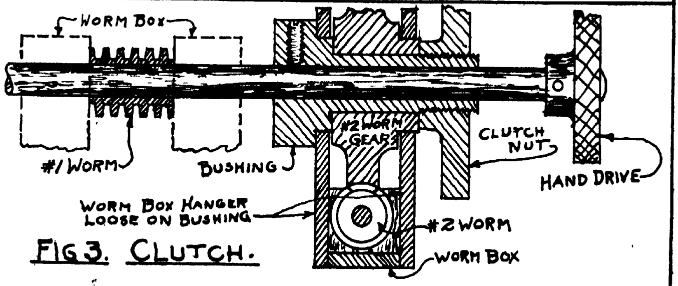


FIG 3. CLUTCH.

driving mechanism. For ordinary purposes Professor King advised that the polar axis of the telescope be set to point toward the apparent celestial pole, and advised the user to choose a rate of speed about one second per hour slower than actual sidereal time. This compensates approximately for the apparent slowing down of the stars' travel for ordinary altitudes in the sky. Therefore we shall choose for our telescope a drive that will rotate the polar axis once in about 86,164 seconds, plus 24 seconds, or a total of 86,188 seconds for a complete revolution.

With the accurately controlled electric current now available, an ideal drive consists of a synchronous motor geared down to give the correct speed to the telescope. This considerable reduction is easily obtained by using several worm drives in the gear train. To make it still easier, motors are now available with double, built-in worm gear reductions which reduce the 1800 r.p.m. of the motor to as low a speed as 1.6 r.p.m.—a reduction of 1120 to 1. Motors so equipped cost about $25.00 (1935).

We shall use the motor specified in Figure 2, which has a reduction of 510 to 1. This, with a 130-tooth worm gear on the polar axis and a 39-tooth worm gear on the worm shaft, gives one complete revolution of the polar axis to 2,585,700 of the motor, in 86,190 seconds. This is 26 seconds more than a sidereal day, and corresponds very closely with Professor King's recommendation.

Worm gear No. 2 is held on its shaft by the nut shown in Figure 3. When released, the gear is free to turn on the shaft, allowing the hand drive to be used for adjustments. When the nut is tightened it clamps the gear against the shoulder on the worm shaft, allowing the motor to drive the telescope.

It has been found advisable to mount the motor on a base separate from the telescope. Unless this is done, even as small a motor as this will set up vibrations which will be very apparent when high powers are used in observing. No method of cushioning or suspension seems to cure this, but it will be entirely avoided if a separate base is used, and if the drive shaft is interrupted by the leather disk shown in Figure 4.

Good photographs generally require manual guiding on both axes, in addition to the motor drive. This is the method used by observatories in photographing star clusters, nebulae, etc. A guide telescope is attached to the main telescope and the observer looks through it and, with the hand control, makes any adjustments necessary to keep the guide star on the cross hairs in his eyepiece. The guide telescope should have a focal length at least as great as the main instrument, and even longer if practicable. It is very essential that the hand controls be within easy reach of the observer.

In conclusion, let me advise against trying to use electric clock motors, which are not nearly powerful enough; or phonograph motors, which, even if synchronous, are usually not self-starting, requiring to be spun to start them. By all means get a good substantial motor, as any other will be likely to cause endless trouble, and will probably prove to be a dead loss in the end. The motor specified in Figure 2 is Type NSR-60 cycles, 1/75 H. P., ball bearing. 3B2247-510. Output shaft vertical, turning counter-clockwise. Made by the Bodine Electric Co., Ohio St. and Oakley Blvd., Chicago, Ill.

Part VI.

METHODS OF SILVERING GLASS

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Cleaning the Surface to be Silvered

This is the most important part of the process, whatever formula is used. The glass surface must be chemically clean. A greasy surface, which has not previously been silvered, should be cleaned with some such solvent as alcohol or ether. Following this, the surface should be scrupulously cleaned with nitric acid.

Make a swab by winding absorbent cotton on the end of a glass spatula or glass rod, with sufficient thickness of cotton so that there will be no danger of scratching the glass with the rod. With such a swab and pure nitric acid to which a little distilled water may be added, clean *every* part of the surface; considerable pressure should be used in rubbing with the swab. Do not let any part of the glass become dry in this process; if it does, swab and clean again.

Rinse off the nitric acid, for which ordinary water may be used at first, followed by distilled (or rain) water.

Finally leave the mirror in a tray or other container, covered with distilled water, until ready to silver. *No part of the mirror should be allowed to become dry.*

After cleaning with nitric acid, many advise a second cleaning with a strong solution of caustic potash, followed by an application of French chalk, and rinsing as above. The nitric acid alone will be found sufficient, provided the cleaning is thoroughly done, and plenty of pressure used in the swabbing.

In commercial silvering many manipulators follow the cleaning with nitric acid by a vigorous swabbing with a saturated solution of stannous chloride ($SnCl_2$), which is carefully rinsed off with warm water. This is regarded as an essential feature in most of the "secret processes" used in the trade.

Purity of Chemicals Used

All chemicals used in the formulae must be of high purity, of the grade known in the trade as C. P.; the use of impure re-agents will result in failure.

Distilled water is best; if this is not available use rain water. In some localities it will be found that the water from the taps will answer instead of distilled water. A test on a small mirror will decide this point. If the solution turns a light pink or blue when the silver nitrate is dissolved in the water, the water is probably too impure for the purpose.

BRASHEAR'S PROCESS

This process is probably used more than any other for silvering the surface of large mirrors used in reflecting telescopes, and laboratory mirrors where a thick coat is desired.

For most work the following proportions will be found adequate:

$$\frac{\text{Square cms.,}}{40} \text{ or } \frac{\text{Square inches}}{6} = \left\{\begin{array}{l}\text{No. of grams}\\ \text{silver nitrate}\\ \text{required}\end{array}\right.$$

For very thick coats, and for *astronomical* mirrors, many prefer a more liberal allowance of silver nitrate, about as follows:

$$\frac{\text{Square cms.,}}{27} \text{ or } \frac{\text{Square inches}}{4} = \left\{\begin{array}{l}\text{No. of grams}\\ \text{silver nitrate}\\ \text{required}\end{array}\right.$$

Caution: In using the Brashear process keep the solutions, and do the silvering, at a temperature of about 15° C. or 59° Fahrenheit. In hot weather it is advisable to use ice to keep the temperature of the solutions below 18° C. (64° Fahrenheit). If warmer than this the resulting coat is apt to be soft, and there is danger of the formation of small amounts of silver fulminate, *which is very explosive.*

The Reducing Solution:

Rock candy	90 grams
Nitric acid (specific gravity 1.22)	4 cc.
Alcohol	175 cc.
Distilled water	1000 cc.

This reducing solution is preferably made up in advance; the older it is, the better it will work. If necessary to use it at once, the action may be improved by boiling it, adding the alcohol after it has cooled.

The Silvering Solutions: (Make up just before silvering)

A	Distilled water	300 cc.
	Silver nitrate	20 grams.
	Strongest ammonia, as may be needed	(see below)
B	Distilled water	100 cc.
	Caustic potash	10 grams.
C	Distilled water	30 cc.
	Silver nitrate	2 grams.

In solution A, after the nitrate is all dissolved, add ammonia gradually. The solution will at once turn a dark brown. Continue adding ammonia, drop by drop toward the close of the process, until the solution just clears up; avoid an excess of ammonia. Then pour in solution B; the mixture will again turn dark brown or black. Again add ammonia, drop by drop toward the close, and stirring constantly, until the solution just clears up again. It should now be a light brown or straw color, but transparent.

Next add slowly, stirring constantly, as much of the reserve silver solu-

tion, C, as the mixture will take up without turning too dark; it is important that the nitrate of silver be in excess. Continue this till there is quite a little suspended matter, which the solution refuses to take up. Filter through absorbent cotton.

When ready to silver, pour into this mixture about 6 cc. of the reducing solution for each gram of silver nitrate used, and pour at once upon the mirror, which has been lying covered by about the same amount of water as is used in the solutions; this water need not be poured off.

The process will be finished in from three to eight minutes, depending on the temperature of the solutions, which should never exceed 18° C. (64° Fahrenheit). It is well to make preliminary tests in small beakers or drinking glasses to get the time necessary as the coat is apt to bleach if process is continued too long. Keep solution in motion so that the thick sediment which forms will not deposit on the silver coat. A *very* light swabbing with loose absorbent cotton, over *every* part of the mirror, will be found advantageous in large mirrors, as soon as the coat begins to form. Avoid exposing the surface to the air for more than a second or two at a time to observe progress.

Get the spent solution off quickly at the close of the process; rinse thoroughly, first with ordinary and then with distilled water; swab lightly with absorbent cotton while rinsing if there is much "bloom" on the surface.

Drying, Burnishing, Etc.

Stand mirror on edge to dry and remove water at edges with blotting-paper.

For front surface silvering, burnish, after mirror is perfectly dry, by making a pad of softest chamois skin wrapped around a wad of cotton. Rub a very little of best optical rouge into this pad, and go over entire surface in circular strokes. Dust mirror and pad occasionally during the burnishing to avoid scratches.

Burnishing is not necessary for back surface silvering, as in ordinary looking glasses. The silver coat may here be covered with one or two coats of shellac and later covered with paint or other protector.

[Editor's Note: The following list, expressed in the customary weights and measures, was calculated specifically for a 6-inch mirror, by Porter.

Reducing Solution: Loaf sugar, 3 oz.; nitric acid, of specific gravity, 1.22, 1/4 oz.; pure grain alcohol, 7 oz.; distilled water, 40 oz. (at druggist's).

Silvering solutions: Solution A—distilled water, 8 oz. (one glass); silver nitrate, 1/2 oz.; strongest ammonia, as may be needed (see text of Bureau of Standards Circular, quoted above). Solution B—distilled water, 4 oz. (1/2 glass); caustic potash, 1/4 oz. Solution C—use one-tenth of solution A, reserved for that purpose. In adding ammonia do not try to dissolve the black flakes. Use 3 1/2 fluid ounces of reducing solution.]

Part VII.

Grinding and Polishing Machines

Whether one chooses to use a machine or not—unless working on disks more than about 16 inches in diameter where it is virtually imperative—is a question the amateur may decide for himself. There are those who, like Ellison, prefer to work by hand, and others whose vote will be cast for the machine. Excellent work may be done by either method.

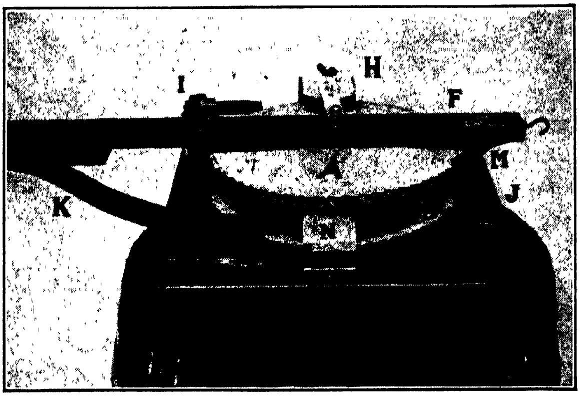


FIGURE 1. LEE'S MACHINE

Many, however, actually enjoy designing and constructing a machine, and especially the satisfaction of sitting back and watching the automaton of their own creation accomplishing the work. In the present chapter several machines are briefly described—briefly, because the accompanying illustrations all but describe them. The worker who is handy enough to build a practical machine will himself be able to supply the minor mechanical details when given a hint by a drawing or photograph, and will perhaps enjoy the job the more if not too minutely instructed. It will prove possible to vary the details to suit one's own ideas and requirements, and there is nearly always room for improvement.

The simplest automatic machine which has come to our attention was constructed in 1927 by John C. Lee. This was described by Mr. Lee, in the *Scientific American*, August, 1927, as follows:

"It is probably unsportsmanlike for the amateur telescope maker to consider anything in the way of a machine to help him with the tedious work of

grinding and polishing his mirror. There are, however, renegades, and I am one of them.

"The pictures, Figures 1 and 2, show a simple form of machine which almost anyone could make in a day or two from material taken from the scrap heap. One of them shows the machine ready for operation, and the other one shows the separate parts.

"What seems to be a novel feature in this machine is the immersion of the rubbing surfaces in the grit or rouge mixtures, thus eliminating the necessity of constant attention.

"Most of the sheet metal work is made of number 22 B. and S. gage galvanized iron.

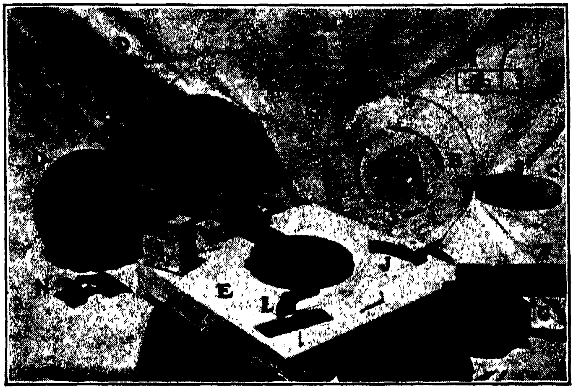


FIGURE 2. PARTS OF LEE'S MACHINE

"The lettered parts are as follows:

A: Disk with 63 teeth cut in the edge to form a ratchet wheel. On the lower side is soldered a dust rim and six clips to grip the mirror holder *C*.

B: Similar to *C* except that it has 60 teeth and the six clips are on the upper side to hold the pan *D*. The lower side has rigidly fastened to it a spindle for insertion in the base *E*.

C: Cup-shaped mirror holder with a rigid spindle, which when assembled passes through disk *A* and connecting rod *F*. The rim on the inside has three pieces of rubber, spaced at regular intervals and fastened with shellac. Over the mirror is placed a disk of rubber (old inner tube) to serve as a cushion.

D: Recessed tray for holding the lap and grinding or polishing mixture.

E: Wooden base with central hardwood turntable.

F: Connecting rod for transmitting a reciprocating motion. (60 strokes a minute is a satisfactory speed.)

G: Wooden block to be fastened to the face plate of a lathe or other rotating device to impart motion.

H: Adjustable guide.

I: Adjustable pawl for turning disk *A*.

J: Pawl to prevent backward motion of disk *B*.

K: Pawl for turning disk *B*.

L: Guide for controlling pawl *K*.

M: Pawl to prevent backward motion of disk *A*

N: Stirring device of hard wood, mounted on a flexible and readily detachable arm.

"An inspection of the pictures will show that the machine is capable of performing all the ordinary hand strokes of grinding and polishing. A practically straight stroke can be imparted by substituting a long arm in place of the short one *H*.

"Pressure is obtained by clamping weights on connecting rod *F*. Fifteen pounds is sufficient up to the finest polishing, when no weight is desirable.

"The barrel on which the machine is mounted serves as an element of safety in case there is a tendency to grip; in this event it will tip. Gripping can be eliminated during the grinding by the use of a grooved lead lap in place of glass.

There is an advantage in adding to the grinding mixture something to increase the density as well as the gravity of the liquid, such as sugar or other inert substance, and thus retard the precipitation of the grits during the grinding process. The stirring device alone is not sufficient for the most satisfactory results.

The laps are raised and lowered in the recessed tray *D* by means of rubber disks, and a thick rubber band is placed around the edge of each lap.

"One 6-inch glass mirror was ground, polished and figured on the machine without any hand rubbing. A 6-inch quartz mirror was made on it up to a polished sphere, and the final figuring was done by hand.

"The device is most satisfactory during the fine grinding and polishing. If a mirror has been overcorrected and is in the form of a hyperboloid or some other monstrosity, it is only necessary to put in a suitably trimmed lap and let the machine run by itself until the desired results are attained."

The Editor has had the privilege of watching Mr. Lee's machine, described above, in action; also of inspecting a creditable quartz mirror it produced. Though simple both in construction and operation, the machine performed steadily and could be left running for long periods without attention.

Four different machines are depicted in R. W. Porter's composite sketch reproduced in Figure 3. The first, labelled *A*, is a three-cornered German machine he used at the Bureau of Standards in Washington, while employed on optical work during the World War. Compounding the crank throws on the two rear crank shaft permits all kinds of strokes, straight, elliptical or

figure eight, on the nearer spindle which carries the work and lap. Machines of this general type are used in the famous Carl Zeiss Works at Jena, Germany.

The second machine in Figure 3, labelled *B*, was designed and constructed by Porter and is the machine he regularly uses. This is a bench machine with a capacity up to 12-inch disks. The crank arm carries a spindle which transmits, through bevel gears at the crankpin to a worm and worm gear at the pin which engages the mirror, a slow rotation of the work in a direction

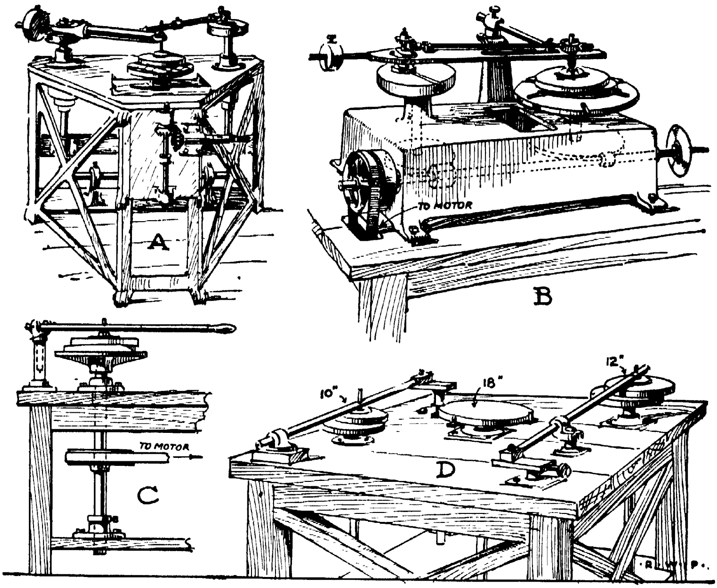


FIGURE 3

Machines for grinding and polishing, described in the text. The beginner frequently labors under the belief that a machine is a necessity if really good work is to be done. This belief is entirely without foundation. Ellison, whose hundreds of high grade mirrors may be found the world over, works by hand and states that he has completed a mirror, from the blank to polishing and figuring, in six hours, a feat which of course requires skill and experience in addition to physical endurance. A machine nevertheless appeals to the mechanically minded, and the sketches shown above are therefore inserted largely as a source of ideas for designs.

opposite to that of the lap below. The machine has polished about 100 mirrors of varying diameters and has been found entirely satisfactory. The sheet iron disk on the right hand end of the worm shaft is for slicing glass.

The third sketch, *C* in Figure 3, depicts the elements of a simple vertical spindle and hand lever, as originally sketched by G. H. Lutz. The handle is universally pivoted at the fulcrum end, and during use it is given a hand motion backward and forward. For disks of 6 inches or more the lap should be revolved slowly, but for small work like eyepiece lenses it may turn at 700 to 1000 R.P.M.

The fourth machine, *D*, was redrawn from a rough sketch by F. M. Hicks. The drawing depicts schematically the three spindles built and used by the "Amateur Telescope Makers of Los Angeles." All three spindles are driven from below by means of electric motor, belts and pulleys. The three grinding

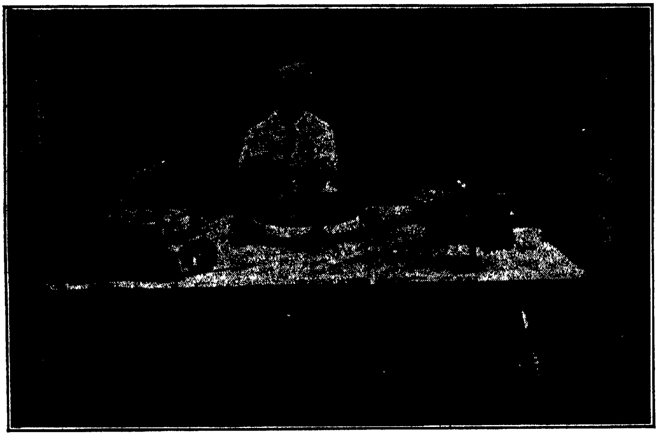


FIGURE 4

A photograph of the three-part machine shown in Figure 3, at D. *It will accommodate disks from 4 to 18 inches in diameter. The man shown is merely adjusting the levers, the machine being automatic.*

tables will take, respectively, 10, 12 and 18 inch disks. The table is of wood, heavily braced and very solid. Figure 4 is a photograph of this table and its attachments.

Finally we come to the Ritchey type of machine designed and used by Professor G. W. Ritchey for grinding, polishing and figuring the 60-inch mirror, shortly previous to 1904, at the Mt. Wilson Observatory. This was described in "Smithsonian Institution Contributions to Knowledge," Volume 34, a work which is now entirely out of print, and rare. The part of this work which describes his machine is quoted below; machines closely similar were used in 1916 in making the 100-inch mirror at Mt. Wilson Observatory (Figure 10), and in 1926 at the Paris Observatory in his experiments on

cellular mirrors. (See the Miscellany.) The fact that he has seen fit to embody the same principles in three successive machines is evidence that the design has proved satisfactory. Though this type is primarily intended for large disks, those who wish to design machines of various capacities will find a close study of it well worth while. The four illustrations, Figures 6, 7, 8 and 9, are reproduced from prints made from the original negatives, and were supplied through the courtesy of Professor S. B. Barrett, Secretary of Yerkes Observatory. Professor Ritchey's description follows:

"The grinding and polishing machines used by the writer are somewhat similar in principle to Dr. Draper's machine, shown in Figure 25 of his book,

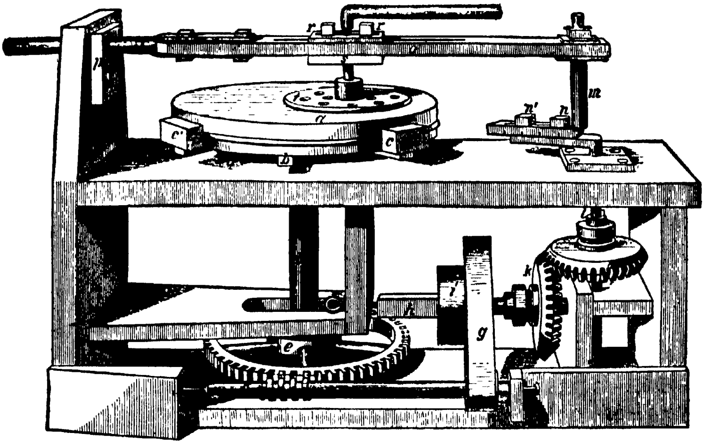


FIGURE 5, THE ANCESTOR

This is the old Draper machine to which Professor Ritchey refers in his description. Older still were the machines of Lassell and Lord Rosse; while Smith's "Compleat System of Opticks," 1738, contains an illustration of Huyghen's machine. Thus, the grinding and polishing machine is about as old as the reflector itself.

but are more elaborate. I shall describe here the machine used in making the 5-foot mirror, both because it embodies most of the essential features of a grinding and polishing machine, and also because it is the only one of my machines of which I have a series of photographs for illustration. A good idea of this machine may be gained from the views of it shown in Figures 6, 7, 8 and 9.

"The massive turntable upon which the glass rests consists of a vertical shaft or axis 5 inches in diameter, carrying at its upper end a very heavy triangular casting, upon which, in turn, is supported the circular plate upon which the glass lies. This plate is of cast iron, weighs 1800 pounds, is 61

inches in diameter, is heavily ribbed on its lower surface, and is connected to its supporting triangle by means of three large leveling screws. The surface of the large plate was turned and then ground approximately flat; two thicknesses of Brussels carpet are laid upon this, and the glass, with its lower surface previously ground flat, rests upon the innumerable springs formed by

Courtesy of Yerkes Observatory

FIGURE 6

The Ritchey machine used at Yerkes Observatory for making the 60 inch mirror destined for Mt. Wilson Observatory. The mirror is shown tilted up, ready for testing.

the looped threads of the carpet. No better support for a glass during grinding and polishing could be desired.

"Three adjustable iron arcs at the edge of the glass serve for centering the latter upon the turntable, and prevent it from slipping laterally.

"The entire turntable, with the heavy frame of wood and metal which supports it, can be turned through 90 degrees about a horizontal axis, thus enabling the optician to turn the glass quickly from the horizontal position which it occupies during grinding and polishing, to a vertical position for testing. This is shown in Figure 6.

"The turntable is slowly rotated on its vertical axis by means of the large pulley below (Figure 7). This rotation is effected by means of belting from the main vertical crankshaft on the east end of the machine; this shaft is well shown at the left in Figure 8. At the upper end of this shaft is the large crank, with adjustable throw or stroke, which moves the large and strong

Courtesy of Yerkes Observatory

FIGURE 7

Another view of the machine shown in Figure 6; also Figures 8 and 9. The large lever across the top extends about 18 inches farther to the left, out of the illustration. Here the grinding tool, a part of which shows, is attached to it by means of a threaded screw which is equipped with a hand wheel permitting vertical adjustment.

main arm to which the grinding and polishing tools are connected, and by means of which they are moved about upon the glass. This I shall always refer to as the main arm. It is a square tube of oak wood, and is strong enough to carry the counterpoising lever shown in Figure 8, and the weight of any of the grinding tools, when fully or partially counterpoised. This main arm also carries the system of pulleys and belts by which the slow rotation of the grinding and polishing tools is rigorously controlled; these, and the manner in which this rotation is effected, are well shown in Figure 8.

"The west end of the main arm consists of a strong steel shaft which slides in a massive bronze swivel-bearing which corresponds to the 'elliptical hole in the oak block p' of Dr. Draper's machine (see his Figure 25). But this bearing is not stationary as in Draper's machine; it is not only mounted on a long slide (which I shall refer to throughout this article as the transverse slide), so that it can be slowly moved for several feet across the west end of the machine by means of a long screw, but this bearing and slide are carried upon a secondary strong arm, which is moved by a secondary crank at the southwest corner of the machine. Unfortunately there is no photograph which shows this part of the machine as it appears when in use; Figures

Courtesy of Yerkes Observatory

FIGURE 8

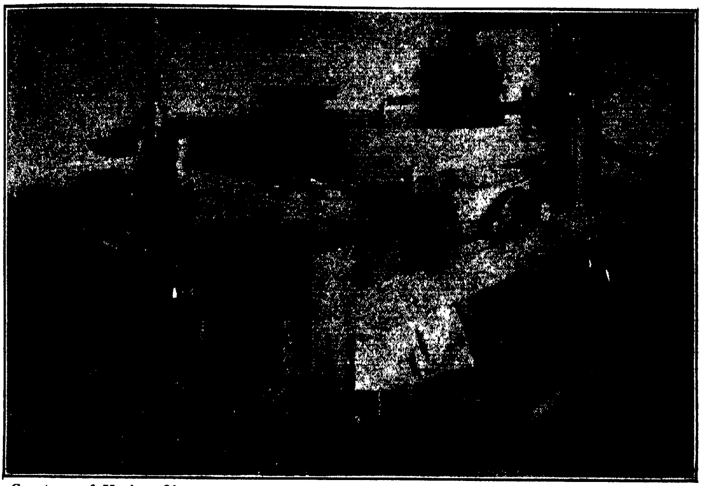
6 and 7 show the secondary crank well, but the secondary arm is shown swung around with one end resting on a bracket on the wall, in order to have it out of the way.

"The arrangement of the west end of the machine is the result of experience with several machines, and is found extremely serviceable and convenient. The long transverse slide on the secondary arm allows the grinding and polishing tools to be placed so as to act on any desired zone of the glass, from the center to the edge; and this setting can be changed as desired while the machine is running. The secondary crank, which turns at the same speed as the large one which drives the main arm, enables the optician to change as desired the width of the (approximately) elliptical

stroke or path of the tool with reference to the length of this stroke; this change is especially desirable when figuring the glass; it is, of course, impossible when only one driving crank is used.

"I regard the transverse slide, or something equivalent to it, as absolutely necessary to the success of a grinding and polishing machine; it will be noticed that its purpose corresponds, in some measure, to that of the long slot in the main arm of Draper's machine. I have used both arrangements and have found the transverse slide to be far more effective and convenient in use; its use will be described in the chapters on grinding and polishing.

"The secondary crank, while very desirable and convenient, for the reason



Courtesy of Yerkes Observatory

FIGURE 9

The attachments are shown swung out of the way, and equipment for edging the mirror is in use as it slowly rotates. Generally a disk of soft steel with carborundum and water, is used for this purpose.

given above, is not indispensable; I have used several smaller machines which have given good results without it.

"The manner in which the grinding and polishing tools are connected to the main arm is shown in Figure 8. A vertical shaft, 1⅜ inches in diameter and 24 inches long, both rotates and slides (vertically) freely in bronze bearings attached to the main arm. The grinding and polishing tools are connected to the lower end of this shaft through the medium of a large universal coupling—a gimbal or Hooke's joint—with two pairs of horizontal pivots at right angles to each other; this allows the tools to rock freely in

all directions in order to follow the curvature of the glass. The tools are lifted, for counterpoising them, by the lever above (see Figure 8), through the medium of the vertical shaft and the universal coupling. In the case of very massive grinding tools of moderate size, like that shown in this illustration, the universal coupling is connected directly to the back of the tool; but in the case of all large tools which are to be used for fine work this connection is made through the medium of a system of bars and triangles, so that the tools are counterpoised without the slightest danger of changing their shape. A small coupling with ball bearings at the upper end of the vertical

Courtesy of Mt. Wilson Observatory

FIGURE 10

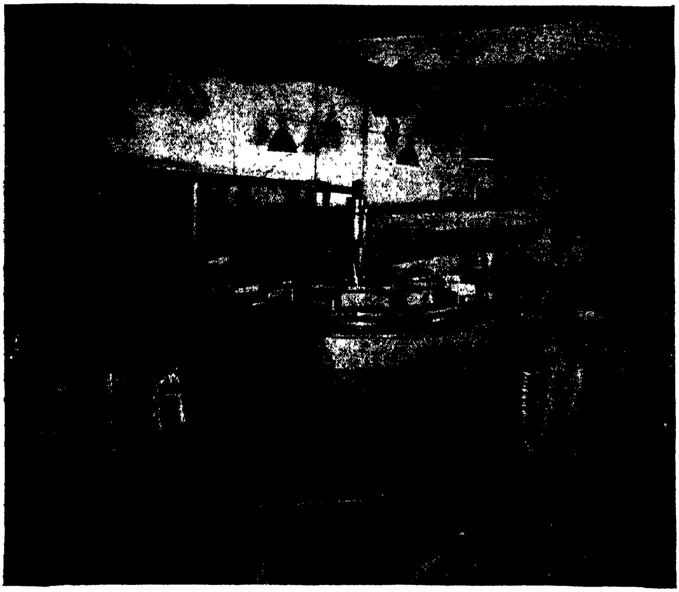
The 100-inch mirror for Mt. Wilson Observatory being finished by Professor Ritchey in the laboratory in nearby Pasadena. Compare the machine used with that shown in the previous four figures.

shaft allows the latter to rotate freely with reference to the link which connects it to the counterpoise lever.

"To recapitulate briefly: This method of connecting the grinding and polishing tools allows them to be controlled in all of the following ways simultaneously: (1) the stroke of the tool is given by the motion of the main arm; (2) the slow rotation of the tool is rigorously controlled by the belting above; (3) the tool is allowed to rock or tip freely by means of the universal coupling, in order that it may follow the curvature of the glass; (4) the tool rises and falls freely by means of the sliding of the $1\frac{3}{8}$-inch vertical shaft in its bearings, in order that it may follow the curvature of the glass; (5) the

tool is counterpoised by means of the lever on the main arm, through the medium of the same vertical shaft and universal coupling.

"In Figure 7 is shown the large lever by which the 5-foot glass, which weighs a ton, is lifted on and off the machine, and by means of which, also, the large grinding tools are handled. One of the full-size grinding tools, weighing 1000 pounds, is shown suspended by the lever. The arrangements are so convenient that the optician alone can do all parts of the work."



A large polishing machine in the Pittsburgh works of J. W. Fecker. "After a blank has been polished on both sides in another machine," Mr. Fecker states, "it is put into this large machine and polished at very low speed with a full-sized polisher, in order to produce a true surface of revolution. After that we start the figuring and parabolizing by the use of smaller polishers, mostly operated by hand." It will be noted that Mr. Fecker mentions polishing a blank on both sides. Many have learned that this is sometimes done and believed it a necessary refinement. Mr. Fecker was asked to explain his reasons for doing it and replied, "Some authorities claim that if the back of the disk is polished the temperature radiation from both sides will be equal—which is probably true until the front surface of the mirror is silvered. We polish both sides of the mirror for one reason alone—so that we can set it up and pass polarized light through it and study the strain figure. After we determine whether or not the annealing is satisfactory, we have no further use for the polished back." This should dispose of a question which is frequently asked.

Part VIII.

CHAPTER I.

Telescope Oculars

By Charles S. Hastings, Ph.D.
Emeritus Professor of Physics at Yale University.

The easiest way to acquire a practical knowledge of oculars, their merits and defects, is to make a few properly directed experiments, such as those described below.

Assume for the moment that we have a good telescope, either refracting or reflecting, of which the focal length is fifteen times the aperture, which is the ordinary ratio for large astronomical telescopes; take a simple plano-convex lens of about three-fourths of an inch focal length and make the following observations:

Experiment I

With the flat side toward the eye it will be seen at once that the extent of the field will depend upon the position of the eye and that at one particular point the field is at its greatest, growing smaller either when the eye advances or recedes. Turning the telescope toward a bright field it will be found that there is, just where the eye should be placed for largest field, a bright circle which is in effect the image of the objective. This we shall call the *ocular circle.* The diameter of the objective, divided by the diameter of this circle, is exactly equal to the magnification of the telescope. As it is easy to measure these diameters, even with no more than a pocket rule and magnifier, within two or three per cent, it enables us to determine the magnification with all necessary precision. But this observation carries us farther toward our goal, for it enables one to eliminate all reference to the focal length of the telescope; in short, if the optical circle is large we are dealing with a low power ocular, if small the ocular rates as a high power.

Observe some convenient object at a distance—a brick wall with well marked courses will serve admirably—and note the defects in the image. These defects may be cataloged because they will yield not only much information but also definitions applicable to all oculars.

(1) Strong prismatic colors will be seen, increasing in intensity as one recedes from the center of the field. If the object observed is light on a dark ground it will be found to be blue on the outer side and red on the inner; if dark on bright ground the order of colors is reversed. This error, perhaps the most objectionable one of all, means that the ocular magnifies blue more than red, and is therefore called *chromatic difference of magnification.*

(2) A line which appears straight when passing through the center of the field becomes curved when displaced from the center; always convex toward the center, the curvature rapidly increases toward edge of field. This error is called *distortion.*

(3) If the telescope is adjusted for best definition at the center of the field, it will be found that the ocular must be displaced inward in order to secure best vision for a region not at the center, in other words, the field is not flat. This error is called *curvature of the field*—not to be confused with (2).

(4) If the telescope be adjusted for a point at a distance from the center of the field it will be found necessary to alter the adjustment in order to secure best vision on a line at right angles through the same point. The brick wall furnishes an easy test of this point. The error is called *oblique astigmatism.*

(5) Observe an object like a thin twig, or a telegraph wire against a bright sky; if the ocular is pushed in, the object will appear orange; if withdrawn it appears blue. If the object is bright on a dark ground—such as a star, real or artificial—the colors will be reversed in order. The colors named must be distinguished from the green and complementary violet which belong to an ordinary achromatic object glass, though not to a reflector. The error is called *chromatic aberration.*.

(6) There is another error, much more difficult to detect, since, in the case of a single lens, it is small, and also because it depends upon the quality of the objective: that is the difference of appearance of a star image inside and outside proper focus. It is called *spherical aberration,* and is easily detected in the familiar Huyghenian ocular.

EXPERIMENT II

Reverse the ocular so that the convex side is toward the eye; then it will be found that all of the above errors are exaggerated except (5) and (6); the former remains unchanged and the latter is lessened.

We are now in a position to detect and explain the errors of more convenient and familiar oculars, since we have not only their names but also experimental knowledge of them. The most celebrated of these is the Huyghenian ocular, since, omitting those used with a micrometer, probably ninety-nine in a hundred employed in the past two centuries are of this type. It is often called a *negative* ocular—a very ill-chosen name because there is nothing negative about it. The term is supposed to convey the fact that one principal focus is between the lenses, which precludes its use with a filar micrometer.

Huyghens was one of the greatest philosophers of all times and his discoveries and inventions are almost innumerable; here, however we are concerned only with the invention named above. He discovered, doubtless by experiment only, as optical theory was not sufficiently advanced, that if the ocular is made of two lenses separated by a distance half as great as the sum of their focal lengths, the worst of all the faults of the ocular, that is, the chromatic difference of magnification, would disappear. Moreover, he knew, just as the foregoing experiments have shown, that the shape of the lens has much to do with the aspect of the field. The final result of his invention was a two-lens ocular as shown in Figure 1, A, with the following prescription: Both lenses plano-convex with plane side toward the eye; the

one next to the eye is called the *eye-lens* and the other the *field-lens.* Focal length of eye-lens 0.5 inch; of field-lens 1.5 inch; separation 1.0 inch.

Such an ocular will yield the same magnification as a single lens of 1-inch focal length and will practically eliminate errors (1) and (2) while (3) and (4) and (5) are little changed; (6), however, is much increased, being 1.5 times as great as that of a lens such as used in Experiment II of like power. It should be emphasized that for low powers—when the ocular circle is more than one-tenth of an inch in diameter, for example—nothing better need be looked for. Moreover, the ocular is easily constructed by the amateur optician. Only when an exceptionally large field, as for a comet-seeker, have I found it advantageous to replace it.

High Power Oculars

Whenever the ocular circle is less than one-tenth of an inch in diameter the ocular in use may be properly styled a high power ocular. If the diameter is half this value we are approaching the limit of useful powers; indeed, with a diameter of about one-sixteenth of an inch the telescope, if

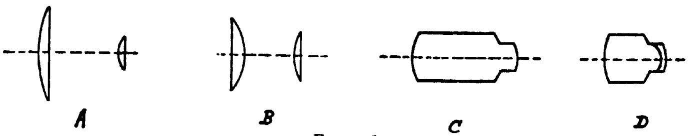


FIGURE 1

A represents a Huyghenian or "negative" ocular, B a Ramsden or "positive" ocular. C is a solid type and D a new solid ocular with a cemented flint glass cap or wafer. All four are described more fully in the next chapter.

quite perfect and if, at the same time, the eye of the observer is of normal acuity, the instrument is practically at its highest efficiency. By this is meant that in a well lighted landscape more fine detail can be seen with this magnification than with one greatly lower or higher.

The reason of this is interesting and instructive. With low powers, provided that the pupil of the eye is as great as the circle itself, the inherent defects of the eye, especially the radial structure of the lens and the spherical aberration, cease to be negligible. If the pupil is smaller than the ocular circle the observer is utilizing only a portion of the aperture; for example, if one is looking at the full Moon with an ocular which gives a diameter of one-fifth of an inch to this circle and the pupil has a diameter one-half as great, the effective aperture is reduced to one-half, and only one-fourth of the transmitted light reaches the retina.

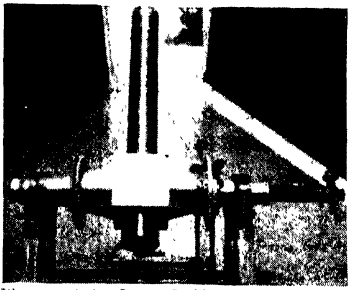
The limitation in the other direction is also easily explained. If the ocular circle is too small, defects of definition due to the finite length of light waves become important. A simple experiment will yield a striking proof of this statement. With a fine needle make a small round hole, say one one-hundredth of an inch in diameter, in a piece of metal foil and observe a well lighted landscape through it; it will be found that much of the

finer detail—light twigs against the sky, for example—will vanish, although there is no lack of light. If one thus observes a distant light at night another peculiar phenomenon will be noticed—the light will appear as a disk surrounded by one or two bright rings. This gives at once the upper useful limit of magnification in a telescope. When a star, under favorable atmospheric conditions, appears as a distinct disk with one or two inconspicuous concentric rings the magnification approaches this limit. An ocular circle of one-thirtieth of an inch may be regarded as conformable to this standard, although higher powers are instructive and sometimes, with close and unequal double stars, they may prove useful.

There is one experiment that everyone interested in telescopes should try; that is to use a negative lens as an ocular. The eye-glass of an opera glass will serve. It will be found that the ocular circle is inside the telescope where the eye can not reach it and therefore the field is greatly restricted. This teaches us something of what Galileo and his contemporary astronomers had to contend with; and it also makes one regret that the discoverer of the satellites of Jupiter did not become acquainted with the first telescope of Lipershey, which was undoubtedly an inverting one, instead of his erecting type.

It is not necessary to extend this chapter by describing my efforts to improve the Huyghenian ocular and my ultimate preferences, since all of this is readily accessible.

There is one thing which may be added because it does not appear in the article cited, and which may stimulate some enthusiastic optician to try a similar experiment. I improved greatly the field in the "solid ocular" (C, Figure 1) by altering the eye-end by a cemented double-convex lens of highly refracting barium crown. Constant and long continued use of this type warrants high commendation.



Photograph by James Stokley

A 3-inch star transit of the broken type (diagonal at elbow and eyepiece in end of horizontal axis) made by Gustavus Wynne Cook of Wynnewood, Pa. It is mainly made of aluminum and weighs 300 pounds.

CHAPTER II.

*Astronomical Oculars**

By Charles S. Hastings

It is a curious and interesting fact that an ocular invented in the seventeenth century should survive in almost universal use until the present day. It was a very remarkable invention by Huyghens, to whom science owes so much both as astronomer and as physicist, and perfectly adapted to the long telescopes with single objectives of his time; how important the invention was one may easily discover by trying to direct a telescope unprovided with circles and finder and supplied with a simple lens for an eyepiece. Notwithstanding this the ocular is a very bad one for use with the modern achromatic objective. To demonstrate the truth of the statement I intend here to describe various oculars with an analysis of their several merits and defects. Moreover, I hope to give such complete details of their construction that amateur telescopists may be prompted to make them for themselves and add to the present limited experience of other types.

It is much to be deplored that there are so few amateur lens makers among Americans. There is a considerable and growing number of enthusiastic makers of mirrors for reflecting telescopes but they appear reluctant in making their own oculars. This is to be regretted because it is immeasurably easier to make a small lens than to make a mirror of significant size, and the making of small lenses is a very fascinating pursuit well within the powers of anyone possessing moderate mechanical aptitude and having command of an ordinary lathe. It is true that for the final grinding and polishing a vertical spindle has marked convenience, but such a tool is not indispensable and if desired it can be easily constructed from a so-called "polishing head" held in stock by most hardware dealers and costing a very little. My own apparatus is thus made and is driven by a small sewing machine motor. One disposed to follow an experiment of this kind must, however, provide for a great reduction in speed of revolution from motor to spindle.

A.† Huyghenian Ocular

This, the most universally used, has many merits. It admits of a large angular field of forty degrees and is very free from distortion, that is to say, a straight line in the field shifted from center to edge retains its appearance of straightness; moreover, the focal length is the same for all colors, hence objects do not assume prismatic colors when shifted from center to edge of the field. This last property may be best defined as freedom from chromatic difference of magnification.

The defects of this form are various. The field is so strongly curved, being

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*Reprinted by permission, from *Popular Astronomy*, issue of June-July, 1926.

†The letters *A*, *B*, *C* and *D*, in the present chapter, refer to the same illustrations which accompany the previous chapter. For a further discussion of eyepieces the reader is referred to the special chapter in Bell's *The Telescope*.—Ed.

convex towards the eye, that only about twenty-five degrees of the field can be regarded as satisfactory; but its most serious defect is in its color error. Ordinarily regarded as achromatic, because it possesses the same focal length for all colors, it has a variation in the position of its focal planes one-half greater than that of a simple lens of the same power. In short, this ocular as described below has its blue image 0.03 inch nearer the eye-lens than that of the orange-red. To make this statement quantitatively accurate it may be paralleled by stating that a change of 0.01 in the index of refraction, which corresponds to this change of color, gives a spread of 0.03 of an inch for the effective color error at the axis. How serious a defect this is appears at once when it is recognized as about ten times the average error of focussing. It follows that a much higher power is required in the ocular for exhausting the definition of a properly corrected objective.

The fact that the first principal focus falls between the lenses is not important when regarded as part of a visual apparatus alone, but it precludes its use with a filar micrometer. This feature is embodied in the name—not very felicitously chosen—negative ocular. More important from our present standpoint is the loss of light reflected back towards the source so that only eighty-three one-hundredths is transmitted.

B. Ramsden Ocular

The necessity of having the first focal plane outside the system for micrometric work prompted Ramsden to the invention of his well known "positive" ocular. This in the hands of different opticians is of somewhat varied construction, but that defined below is a copy of one made by the famous English optician Dolland which has been in the possession of Yale University for nearly a century. Probably it cannot be improved upon.

The qualities of this ocular can be briefly stated. Its permissible field of forty degrees is large, but satisfactory vision is limited to about twenty-five degrees because of the marked chromatic difference of magnification. It is very free from distortion and the field is less curved than that of the Huyghenian; also the error which we have styled chromatic spread of the focal distance is reduced by one-half, a distinct improvement. On the whole this form must be rated superior to the preceding one, for axial vision at any rate, although having the same number of free surfaces it does not surpass it in transparency.

C. Solid Ocular

The origin of this form is quite unknown to me. It is true that it was patented about the middle of the last century by Tolles as an eyepiece for the microscope, a use which would be difficult to defend, but a lens maker who had been employed by both Tolles and his predecessor, Spencer, assured me that it was very much older than assumed. It was a description of this ocular by Mr. Stendicke, the lens maker alluded to, which led me while still a school boy to make many experiments with it. Later experience of many years has proved its appreciable superiority to more familiar types. Its defects are obvious. Its field is small—I have been accustomed to restrict the angular field, by a dia-

phragm in lower powers and by the containing cell in the higher, to a little more than thirty degrees, of which only the central twenty could be deemed thoroughly good. It is not free from distortion but the central field is essentially flat and there is no chromatic difference of magnification. The faults are more than compensated by absolute sharpness of definition and a transparency ten per cent greater than that of a two lens system. For many years I was entirely content with these oculars, of which I made a set having focal lengths of three-fourths, one-half, one-third, one-quarter and one-fifth of an inch. The highest power was of infrequent use of course, and any much lower power than that of the first in the series would fail to exhaust the definition of a thoroughly good objective and therefore fail to exhibit superiority to familiar types. At present I have discarded this form for that to be described immediately, except one of a half inch focal length into which, just where the shoulder appears in the illustrative sketch, I have replaced a portion of the crown glass by a properly chosen disk of dark, neutral tinted glass. This, with the customary Herschel reflecting wedge, makes an ideal system for the study of the surface of the sun, since the faults named above are of no consequence in this case. A copy of this is recommended with confidence.

D. A New Solid Ocular

Several years ago it occurred to me that it might be possible to make an ocular having all the excellences of those already described, provided that the simplification of a single variety of glass were abandoned. The success of the effort is unexpectedly great. This type, which is fully described below, is positive and can thus be used with a filar micrometer. It is not entirely without distortion but the exceptional flatness of the large angular field more than counterbalances this defect, a defect wholly unrecognizable in ordinary astronomical use.

The materials used in these oculars are an ordinary crown glass of a mean index of refraction of 1.5137 and an ordinary flint of mean index 1.6153, the latter only employed for the small cap at the eye end of the ocular. The relative dispersion of the two materials is 1.93. Such glasses are readily procured; moreover, it is obvious that a departure from these constants by a unit in the fourth decimal may be ignored as giving rise to less than the inevitable errors of even careful construction.

The radii and thicknesses (or separations) are given in the table.

Tables of Constants for Construction

	A	B	C	D
r_1	+1.085	∞	+0.675	+0.871
r_2	∞	0.801	—0.421	—0.240
r_3	+0.381	+0.727		—0.509
r_4	∞	∞		
t_1	0.18	0.20	1.60	1.16
t_2	1.18	0.77		.07
t_3	0.08	0.10		

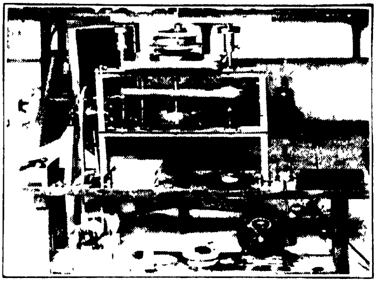
This ends our immediate task but certain remarks may be added either to encourage the hoped-for convert to amateur optics or to add to the store of practical knowledge of users of astronomical telescopes.

First, I suggest that a focal length of three-quarters of an inch would be better for an initial trial, as rather easier to make than either high or low powers. Second, I wish to refute the general supposition that a plane surface is more difficult to make than a curved one. There is no more difficulty in securing a surface of zero curvature to one one-hundredth than a like accuracy in the case of any other named curvature; it is only the fact that plane surfaces are so often employed in oblique reflection, where a precision much greater than that named is necessary, that gives rise to the belief. In the flat surfaces of the oculars described the maker need have no hesitation in making them, with appropriate handles, just as he would the convex ones.

In certain cases a field as large as possible is very desirable, as in comet seeking for example. Nothing else known to me is as good in this respect as an ocular which I designed at the request of the late Mr. McDowell and of which, I believe, he or his successors have made many.

I venture to add the following under the impression that the Herschel wedge is not nearly as much used as it should be. With it Venus, so unsatisfactory an object in a dark, or darkening sky, is a delightful study. Then the moon also, except when a rather slender crescent, is much pleasanter to view with this accessory. Ordinarily this object is so brilliant that the pupil of the eye is contracted so that only part, perhaps a small part, of the objective is effective, which may be the cause of a prevalent impression that the moon is too easy an object to afford a test for the excellence of a telescope.

Yale University, New Haven, Connecticut.



A grinding and polishing machine of the Hindle type (see English Mechanics, 1923) made by Dr. K. Nakamura of the Astronomical Observatory of the Imperial University at Kyoto, Japan.

Part IX.

SOLAR RESEARCH FOR AMATEURS

By George Ellery Hale, Sc.D.
Honorary Director, Mount Wilson Observatory of the Carnegie Institution

CHAPTER I.

Sun-spots, Prominences and Flocculi

No chapters in the history of science are more inspiring than those that recount the discoveries of the amateur. Hampered, it may be, by lack of equipment, situated where conditions for research are not of the best, and often compelled to devote his best hours to other pursuits, the amateur, rising above all discouragement, has continued to pour a flood of new ideas and significant observations into the ever-widening sea of scientific knowledge. Many a great name is associated with a modest beginning, and many a discovery has been made with inexpensive apparatus. Intense interest and persistent purpose naturally bring their own reward.

The amateur thus has a great advantage over the perfunctory toiler, driven into research by someone who thought it might prove interesting, or lured on by a desire for fame or fortune. His eye is not fixed on patents or prizes, decorations or degrees. He works because he cannot help it, impelled by a genuine love for his subject and inspired by an irresistible influence, which he seeks neither to justify nor to explain. His reward lies in the work itself and in the hope that it may contribute something to the advancement of knowledge. If there is any means of deriving greater satisfaction from personal effort one must go a long way to find it.

It naturally follows that the world owes an immense debt to the amateur. His compelling interest, never flagging through the years, often leads to important advances. Thus, Schwabe, the apothecary of Dessau, recording sun-spots day after day for forty-three years with his small but "imperturbable telescope," discovered that their number waxes and wanes in the now familiar sun-spot period. Burnham, busy all day as a Chicago court stenographer, discovered nearly five hundred new double stars in his back yard with a 6-inch telescope. Huggins, in spite of the smoke and fog of London, borrowed instruments from the Royal Society and laid the foundations of astrophysics. Herschel, the organist of Bath; Barnard, the Nashville photographer; Lockyer, the War Office clerk; Bond, the watchmaker of Maine; Schumann, the Leipzig machinist; and many others, limited in time or means, have also left their names in the permanent roll of scientific discoverers. Darwin, Faraday and Rayleigh, though they gave their whole lives to research, were essentially amateurs, members of a guild devoted supremely to science and never to be confused with the idling dilettantes of the popular imagination.

While it is still possible in many fields to contribute to knowledge with the aid of small instruments of standard design, the wise amateur quickly takes advantage of favorable opportunities to enter untrodden territory. Thus while routine observations of variable stars visible with a small telescope are very valuable, the amateur who attaches a thermocouple or photo-electric cell to his equatorial can detect and measure much smaller light-variations than the eye can see, and thus discover new and important phenomena. The work

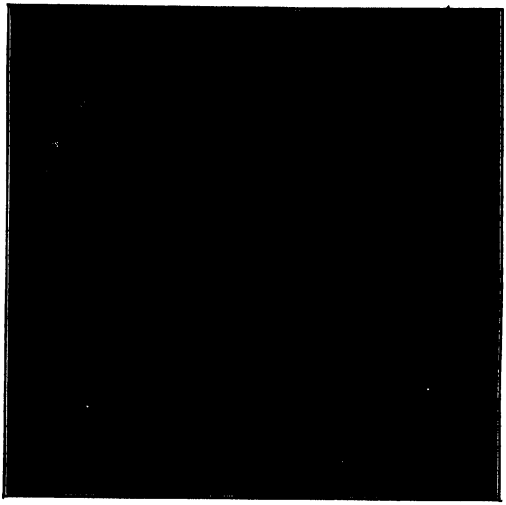


FIGURE 1

Solar prominences photographed in full sunlight with the spectroheliograph. Taken on Mount Wilson with the red hydrogen line (H α), September 21, 1909. (The Sun's disk was covered with a circular metallic screen).

of Stebbins is a fine illustration of this. A similar opportunity for entirely new work, due to the recent development of the spectrohelioscope, now exists in the field of solar research.

The Varied Interest of Solar Research

From whatever angle you look at it, the Sun offers interesting and remarkable subjects for investigation. Unlike most celestial objects, the brilliant and spectacular phenomena of its atmosphere are never twice alike, and the most violent outbursts of terrestrial volcanoes are tame affairs in comparison

with solar explosions. In order to gain any conception of the fantastic beauty of solar prominences it is necessary to see them in action. As Secchi has said in his book on the Sun, it is impossible to reproduce "the vivacity of color of these enormous masses, or to depict their rapid motions when they are shot by eruptions from the interior above the surface of the Sun. The best drawings are inert and lifeless when compared with the actual phenomena. These incandescent masses are vivified by internal forces which seem to endow them with life; they glow with intense brilliancy, and their colors are so characteristic that they enable us to determine spectroscopically the chemical nature of their constituent gases."

Such brilliant phenomena are striking enough in themselves, but their relationship to terrestrial disturbances makes them doubly important. If you

FIGURE 2

Slowly changing or quiescent prominence, 110,000 miles high. Photographed at Mount Wilson with the H α line, June 10, 1917.

are interested in radio, or the aurora, or terrestrial magnetism, you will want to learn the source of the electrified particles which are shot from the Sun into the earth's atmosphere, where they arouse the Northern Lights, initiate magnetic storms, affect radio transmission, produce powerful earth currents in telegraph lines, and sometimes puncture Atlantic cables. They are popularly supposed to come from sun-spots, but some of the largest spots produce no such effects and attention should be directed to the occasional eruptions, occurring on the disk near certain types of sun-spots, which the spectrohelioscope now renders visible.

If the nature and evolution of the stars appeal to you especially, remember that the Sun is the only star near enough the Earth to be studied in detail. To see the other stars as we do the Sun, to discern their huge disks, the spots on their surface, the flames in their atmosphere, it would be necessary to

approach them closely, and there is no prospect that any telescope, however powerful, will ever make this possible. The larger and more perfect the instrument and the better the atmospheric conditions, the smaller their needle-point images appear.

How fortunate, then, that one star is so near at hand! This neighboring object, our own Sun, is proved in a score of ways to be a perfectly typical star, similar in chemical composition, in size and in structure to millions of other stars in the remote distances of space. It is so near us that any telescope will show its disk and the spots that come and go on its surface. These and its other phenomena are most varied in character, constantly changing in number and in form, and suggesting problems of every kind for solution.

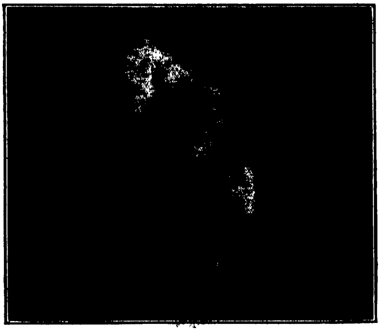


FIGURE 3A

Eruptive prominence, photographed with the Kenwood spectroheliograph, Chicago, March 25, 1895, 10h 40m A. M. Height of prominence, 162,000 miles. Compare with Figure 3B.

Moreover, with the aid of a spectrohelioscope, the amateur will be able to observe, not merely the spectacular outbursts of the chromosphere and prominences encircling the Sun's circumference, but also the little explored region of the solar atmosphere now visible in projection against the disk. Here is a new field, open to amateurs, for discoveries of prime importance, which will aid in solving many puzzling problems of solar and stellar physics.

The Sun may also be regarded in still another aspect, the importance of which has recently been greatly enhanced by the revolutionary progress of physics and chemistry and the rise of the Einstein theory of relativity. In an article on "The Sun as a Research Laboratory"* I have recently pointed out some of the fundamental advances in physics which are the direct result of

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* *Journal of the Franklin Institute*, July, 1927.

solar discoveries. As a matter of fact, the Sun is an immense furnace, with a surface temperature of about 6,000° C. and an internal temperature reaching millions of degrees, sufficient to strip the atoms wholly or partially of their electrons. Between this inner region and the visible surface of the photosphere the chemical elements recover most of their electrons, and we can observe their luminous vapors at various levels in the solar atmosphere under a wide range of conditions, which throw much light on the nature of matter. Thus the establishment of the fundamental principles of spectrum analysis, the discovery of the important element helium, and the first clue (through Lock-

FIGURE 3B

The prominence shown in Figure 3A, photographed at 10h 58m. Height of prominence, 281,000 miles.

yer's detection of the "enhanced" lines) to the modern theory of the constitution of matter, are all results of solar research. For other illustrations I must refer the reader to my Franklin Institute paper.

All of the solar phenomena I have mentioned are easily within the reach of the amateur. If lucky enough to have access to a small machine shop, he can build his own instruments and most of the optical parts. If not, he may purchase his entire equipment at moderate cost or buy only the optical parts and employ a local machinist to do any of the machine work that is beyond his own capacity.

Photography of the Solar Atmosphere

The classic discovery of Janssen and Lockyer in 1868, which made possible daily observation, in full sunlight, of the prominences previously visible only during total eclipses, aroused widespread interest in solar research. Fascinated by this advance, and dimly conscious of the boundless other possibilities of the spectroscope, I began solar work as a boy in 1883.

Six years later it occurred to me (as it had occurred to others) that by building up an image of the prominences upon a sensitive plate with the light of hydrogen or of calcium, I might photograph them without an eclipse. This

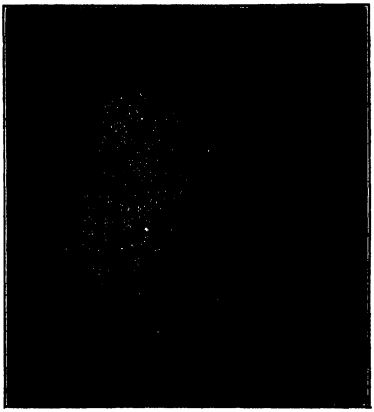

Figure 4

Direct photograph of the Sun, September 27, 1926. (Mount Wilson.)

I succeeded later in doing with a spectroscope, provided with a second slit instead of an eyepiece, through which a hydrogen or calcium line passed to the plate. When the slit of the spectroscope was moved slowly across the Sun, a complete image of all the prominences was built up on the plate by countless adjoining images of the narrow second slit. The bright light of the disk was excluded by a circular metal screen, and the encircling prominences were shown as distinctly as in photographs of total solar eclipses.

The next logical move (in 1892) was to try the same scheme for photographing the disk, where the calcium lines (H and K in the extreme violet) were known to be bright in many places. The spectroheliograph, as I had named the instrument, at once disclosed large bright clouds of calcium vapor (flocculi) in the solar atmosphere, which have since been extensively investi-

gated by Evershed, Deslandres, St. John, and others. These bright flocculi lie at a low level, and do not project above the Sun's edge (limb) as prominences. Later, at the Yerkes Observatory, we found it possible to photograph the prominences projected against the disk as dark flocculi. They are generally dark because the hydrogen or calcium gas is comparatively cool at high levels, and thus absorbs the light from the hotter region below. The same plates also show the bright (hotter) gases at lower levels.

In 1908 the Sun's disk was first photographed at Mount Wilson with the red hydrogen line $H\alpha$, and great vortices or cyclonic storms were discovered

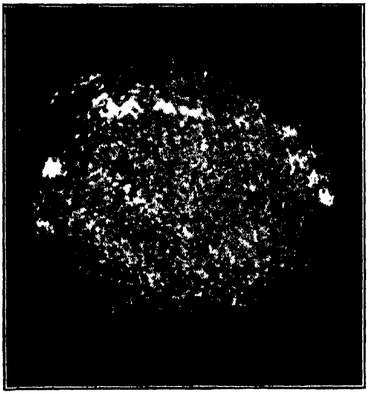

FIGURE 5

The calcium flocculi, photographed with the calcium line K, September 27, 1926. (Compare with Figure 4.)

in the upper hydrogen atmosphere. These were found to center over sunspots, and soon led to the detection with the spectroscope of strong magnetic fields in all spots.

This brief reference to the photographic registration of the chief phenomena of the solar atmosphere is necessary to a comprehension of the new work of the spectroheliscope. The reader who is interested in the details should consult the original papers and also the many publications of Deslandres, Evershed, St. John, and others who have made many discoveries and important contributions in this field of research.*

* Most of these papers may be found in the journals *Astronomy and Astrophysics*, *Astrophysical Journal*, *Comptes Rendus* of the Paris Academy of Sciences, *Monthly Notices* of the Royal Astronomical Society, and in the Publications of the Meudon, Kodaikanal, Yerkes, and Mount Wilson Observatories.

Our daily series of photographs of the solar atmosphere, begun at the Kenwood Observatory in 1891 and continued later at the Yerkes and Mount Wilson Observatories, contains many thousands of plates of the prominences and flocculi. Familiarity with these results has served to enhance my enthusiasm for the new possibilities recently opened by the spectrohelioscope.

New Opportunities for the Amateur

The spectroheliograph, as already stated, builds up its monochromatic image gradually, slit-width by slit-width, as the slit moves slowly across the

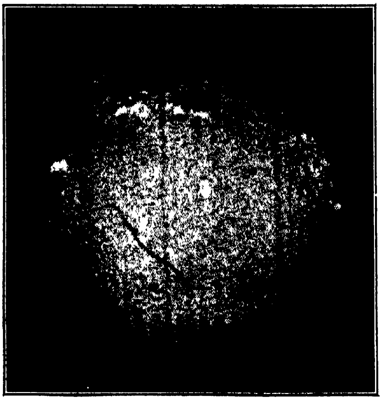

Figure 6

The hydrogen flocculi, photographed with the red hydrogen H α, September 27, 1926. (Compare with Figures 4 and 5, taken nearly simultaneously.)

Sun. The photographic plate, as it were, thus "sees" at any instant only a narrow strip across the solar image two or three thousandths of an inch wide, which it faithfully records, in its varied intensity, as an element in a composite image. A different mechanical arrangement permits the same idea to be employed in revealing a large area of the hydrogen atmosphere directly to the eye. It is only necessary to utilize the well-known principle of the persistence of vision.

The first slit of the spectroscope, on which the Sun's image is formed, and the second slit, on which the red hydrogen line falls, are so connected that when the first slit moves, the second slit also moves in such a direction and at such a rate as to remain exactly upon the displaced hydrogen line. Then,

if the slits are rapidly oscillated to and fro across a portion of the solar image, this region will be seen in hydrogen light through an eyepiece focused on the second slit.

It is astonishing how this simple method, which was tried (but discarded) by Young in 1870 for observing the prominences at the limb, seems suddenly to bring to life the flocculi on the disk, which appear fixed and inert on photographic plates. There are several reasons for this. As the photographer

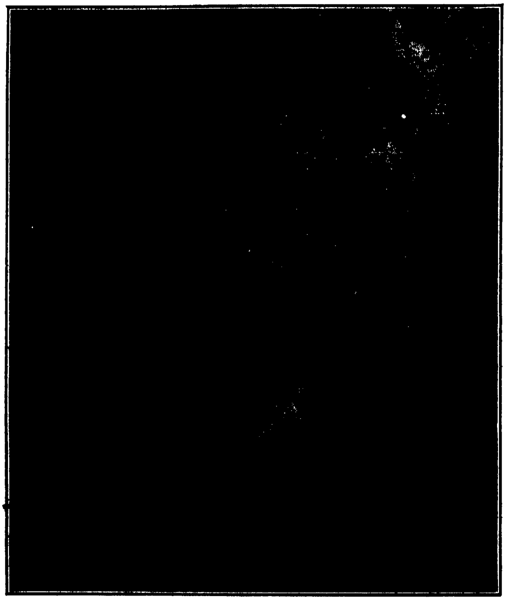

FIGURE 7

Bright and dark hydrogen flocculi, photographed with the red hydrogen line H a, September 9, 1915. (Mount Wilson.)

using a spectroheliograph cannot see what is happening, he makes his exposures in a routine way and thus almost invariably fails to catch the successive phases of remarkable short-lived phenomena that often afford marvelous spectacles to the visual observer, who can pick out at a glance the most interesting and most active regions. Thus I have repeatedly seen with the spectrohelioscope the swift flow toward sun-spots of masses of hydrogen larger

than the Earth, adequately recorded only once with the spectroheliograph in a period of twenty years.

But the spectrohelioscope has another more important advantage, which permits the observer instantly to interpret phenomena missed altogether by the spectroheliograph, or so incompletely recorded that their interpretation remains obscure. This is due to the use of the "line-shifter", an adjustable plate of plane-parallel glass behind the oscillating second-slit, which permits the observer to set any part of the red hydrogen line or its

FIGURE 8

Counter clockwise (N) and clockwise (S) hydrogen whirls associated with sun-spots in the northern and southern hemispheres of the Sun, September 9, 1908. (Mount Wilson.)

wings on the slit during observation. In this way he can observe the form of the flocculus given by any part of the line, which is greatly distorted to the violet or red if the hydrogen is moving with high velocity toward or away from the Earth.

Lockyer and Young long ago saw and described the strange "motion forms" thus produced (Figure 10). The bulge of the C (now called $H\alpha$) line toward the violet observed by Young on August 5, 1872, meant that the

hydrogen gas at a point near an active sun-spot was approaching the Earth at a velocity of about 120 miles per second. Thus if a series of photographs of the *H α* line is made, with the spectrograph slit stationary at many successive sections across such an eruption, the measured displacements of the line will give the radial velocity at the corresponding positions of the slit. This is the principle of Deslandres's "velocity spectrograph".

The spectrohelioscope is far quicker in action and its results are instantly interpreted. Imagine an arch of hydrogen, representing the trajectory of masses of gas continually shooting along the same path near the middle of the Sun. Like a projectile, the gas moves rapidly upward, curves over and travels nearly parallel to the surface, and then falls, curving back toward the

FIGURE 9

Complex hydrogen whirls associated with a large bipolar sun-spot, August 29, 1924. (Mount Wilson.)

surface. Thus in the spectroscope the *H α* line would appear twisted toward the violet at the point of eruption, less and less displaced nearing the center of the arch (where the velocity in the direction of the Earth becomes zero), and increasingly displaced toward the red as the descending branch of the arch is approached. As the projection of such an arch against the surface usually appears curved, and as its form cannot be seen at all without a spectrohelioscope, the task of photographing the *H α* line at several points along the arch, measuring its distortions at all these points on the photographs and interpreting the results would naturally take considerable time. Mean-

while the phenomenon may have passed through several stages and perhaps ceased altogether.

With the spectroheliioscope the whole analysis can often be completed in a few seconds. As the *H α* line is moved across the oscillating slit the darkest spot (maximum of intensity) of the arch is seen to move from its origin at the point of eruption (violet side of *H α*) toward the center of the arch (center of *H α*) and thence to the point of fall (red side of *H α*). By reading the divided circle of the line-shifter at these points the corresponding radial velocities are obtained at once. Perhaps the most beautiful application of this method is in the measurement of the flow of hydrogen into the vortices centering in sun-spots.

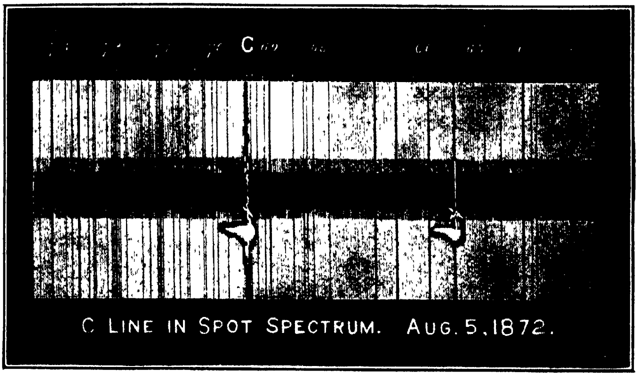

FIGURE 10

Red hydrogen (C or H α) in sun-spot spectrum, as observed by Young on August 5, 1872. The distortion is due to motion of the hydrogen in the line of sight of about 120 miles per second. (From Young, "The Sun," 1884.)

CHAPTER II.

A Simple Solar Telescope and Spectrohelioscope

As explained in the last chapter, some of the most spectacular and beautiful phenomena in the heavens are visible daily in the solar atmosphere. These have so recently become accessible to visual observation that they are but little known, and thus offer promising opportunities for discovery to amateur astronomers. The purpose of this chapter is to explain the construction of the simple instruments necessary to observe them.

Solar Telescope

The telescope required is of the coelostat type, giving a fixed solar image 2 inches in diameter for study with a spectrohelioscope (Figure 11).

The coelostat consists of a plane mirror* of plate glass, 5½ inches in diameter and ½ inch thick, mounted with its surface parallel to the Earth's axis and uniformly rotated by an ordinary (two dollar) clock movement at the rate of one complete revolution in 48 hours.

The parallel rays of sunlight reflected from the silvered front surface of the coelostat mirror fall on a second mirror of plate glass, 4½ inches in diameter and ½ inch thick, mounted in a fork, and provided with slow-motion screws controlled by the observer with rods or cords. This mirror is fixed during observation, but the slow motions permit the observer to move it sufficiently to bring any point on the Sun's disk or circumference to the center of the slit of the spectrohelioscope.

These two mirrors, of course, do not form an image of the Sun. They serve merely to send the parallel rays in a chosen direction (usually north) and to hold them there during observation. The solar image is formed by a single plano-convex lens 3 or 4 inches in diameter and of 18 feet focal length, mounted on a support which can be moved north or south with a coarse screw by the observer for focusing the image on the slit. Such a lens is suitable only for observations with monochromatic light. An achromatic lens is needed for direct observations of sun-spots in white light.†

The coelostat, second mirror, and lens are shown in Figure 12, mounted on a wooden tripod south of a small garage containing the spectrohelioscope. For permanent use a brick or concrete pier, covered with a small wooden house easily removable when observations are to be made, should be erected as a more stable base. The coelostat may stand either east or west of the second mirror support (out of its shadow), but on account of the varying

* The front surfaces of the coelostat and second mirrors should be plane to about one-quarter of a wavelength.

† A small telescope having an achromatic lens one or two inches in diameter, with eyepiece permitting a solar image from four to six inches in diameter to be projected upon a white card for recording the positions of sun-spots, will serve as a useful auxiliary. The larger spots can be fairly well seen, however, on the 2-inch image given by the single lens, especially if it is looked at on a white card through dark spectacles supplemented by a piece of red glass.

altitude of the Sun, it must be moved north or south and fixed for any given date at a point where the reflected beam falls on the center of the second mirror. The beam is then maintained in place by the driving clock.

The Spectrohelioscope*

The spectrohelioscope is merely a long-focus spectroscope, provided with a pair of rapidly oscillating slits affording a view of a portion of the Sun's

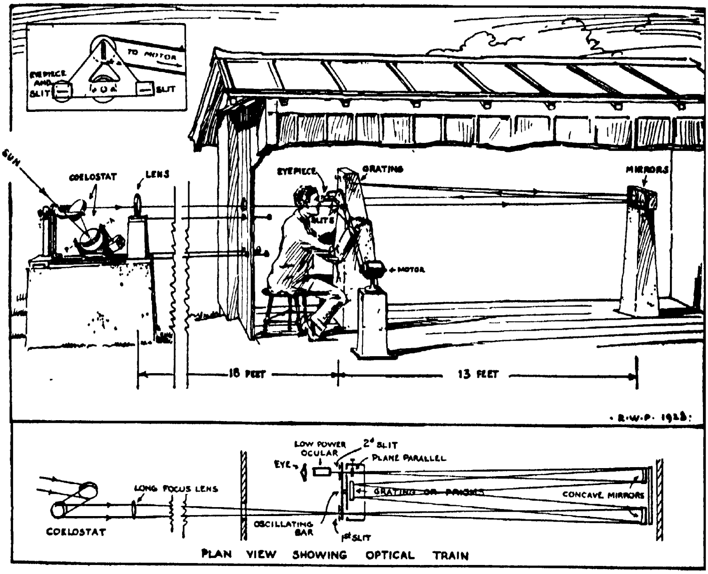

FIGURE 11

Perspective and plan of solar telescope and spectrohelioscope, showing path of the rays used in forming a red (H a) hydrogen image of a part of the solar atmosphere. Drawing by Russell W. Porter.

atmosphere in the monochromatic light of the red hydrogen line known as *H a*. It gives such an image of the Sun as might be obtained through a red screen (if such could be made), transmitting no light except that due to this hydrogen line.

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* See the following papers by the writer: "The Spectrohelioscope," *Proceedings of the National Academy of Sciences*, *10*, 361, 1924; "The Spectrohelioscope," *Publications of the Astronomical Society of the Pacific*, *38*, 96, 1926; "Some New Possibilities in Solar Research," *Nature*, July 3, 1926; "The Fields of Force in the Atmosphere of the Sun," *Nature*, May 14, 1927.

An ordinary spectroscope consists of a narrow slit, a (collimating) lens for making the divergent rays from the slit parallel, a grating (or one or more prisms), and a second lens for forming an image of the spectrum, which is examined by the observer with an eyepiece. The grating is a plane surface of polished speculum metal, on which about 15,000 lines per inch are ruled with a diamond. This diffracts the incident light, and produces a number of spectra resembling those given by prisms.

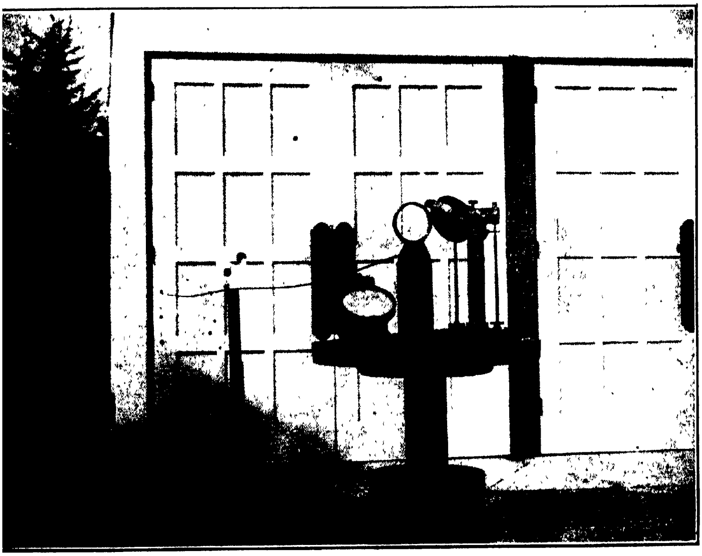


FIGURE 12

The small solar telescope employed in the experiments at Pasadena. The coelostat mirror at the left, driven by clockwork, reflects the sunlight to the second mirror which is provided with slow-motion screws for directing the solar image. This is formed by the simple lens (center), adjustable by a screw for focusing the image on the slit of the spectroheliosocope 18 feet away, within the building.

In the present instrument two spherical concave mirrors, of 2 inches aperture and 18 feet focal length, mounted upon a single support permitting them to be focused by a screw, are used in place of lenses. Light from the solar image falls upon the collimating mirror 18 feet away, and is returned (by a slight inclination of the mirror) to the grating or prisms mounted behind and above the slits. The red ($H\alpha$) region of the spectrum thus formed, falling upon the second concave mirror, is reflected to a sharp focus at a point near

the first slit. Here it falls upon a second slit, adjusted so as to coincide with the center of the $H\alpha$ line. (See bottom diagram in Figure 11.)

The operation of the instrument will now be evident. If the first slit, on which the solar image is focused, is moved in the plane of dispersion, the spectrum will move a corresponding distance. To remain on the line, the second slit must be displaced accordingly. The first and second slits are therefore carried at the opposite ends of a very light metallic bar, mounted on a bearing halfway between them. This bar is oscillated rapidly by a small electric motor, through an amplitude (usually about a quarter of an inch) which is limited by the brightness of the spectrum. The observer, looking through the oscillating second slit, which remains exactly on the $H\alpha$ line, sees by persistence of vision a hydrogen image of a portion of the Sun. This may

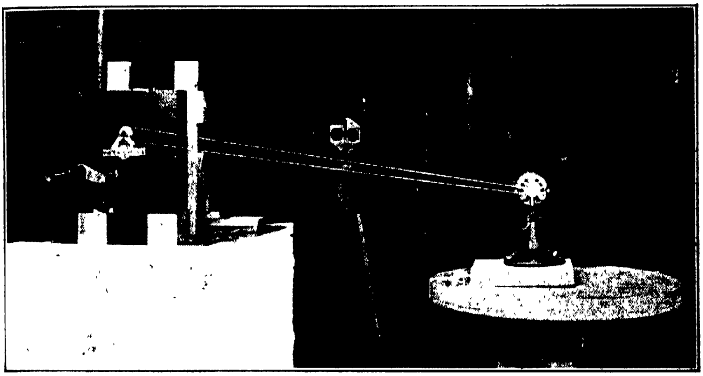


FIGURE 13

Simplest form of spectrohelioscope, of 13 feet focal length. Sunlight passing through the first slit (right) falls on the collimating mirror, which returns a parallel beam to the grating mounted above the slits, behind the casing. An image of the H a line of hydrogen in the first order spectrum is formed by the left concave mirror on the second slit. When the slits are rapidly oscillated by the motor, a portion of the solar atmosphere is seen in hydrogen light through the eyepiece on the left (here turned aside to show the second slit).

include a part of the limb, where a prominence appears bright against the sky, and at the same time a part of the disk, upon which a portion of the same prominence may extend as a dark flocculus.

High velocities in the line of sight produce distortions of the $H\alpha$ line, toward the violet when the gas is approaching, toward the red when it is receding. To see a mass of hydrogen receding at a velocity of, say, sixty kilometers a second the second slit must be set, not on the normal position of the $H\alpha$ line, but at a position completely outside of it toward the red. A simple "line-shifter" is employed for this purpose. A graduated arc indicates

the displacement of the line from the zero position, and thus gives the radial velocity of the portion of the flocculus under observation.

In the above design the slits are only $8\frac{1}{2}$ inches apart. They are therefore mounted horizontally, so as to permit direct observation through the second slit by the right eye without obstruction of the solar image on the first slit by the observer's head. The bar that carries them, like the slits themselves, is extremely light and stiff. An upward extension of this bar is pierced by a fibre-lined vertical groove, in which a steel pin, fixed eccentrically in the head of a horizontal shaft, serves as the driving device. A small electric motor,

FIGURE 14

The oscillating slits, eyepiece, and grating holder, on temporary wooden supports.

belted to a pulley on this shaft, causes the slits to make thirty or forty single oscillations per second. The amplitude is about a quarter of an inch or less, and the motion is smooth and quiet, though there is a slight flicker unless a higher speed is used, which is likely to cause vibration of the grating, unless this is very firmly mounted on an independent support. However, a little flicker does no harm, and is soon forgotten by the observer.

The second slit is viewed through a positive eyepiece magnifying from two to four diameters. The line-shifter, a strip of plane parallel glass, is mounted behind the second slit on a short shaft, provided with a large milled head for

easy rotation by the observer and a divided arc showing the displacement in angstroms or the equivalent radial velocity. An important adjunct is a screen to prevent the diffuse light of the collimating mirror from reaching the eye of the observer.

Similar protection against the glare of the bright solar image on the first slit should be provided, and a tube large enough to prevent reflections from its inner walls should extend from the slit to the opening through which the sunlight enters the building. In fact, the observing room should be as dark as possible.

I have found by experiment that with slits 0.004 inch wide, oscillating with an amplitude of $\frac{3}{16}$ inch, the bright and dark hydrogen flocculi can be well

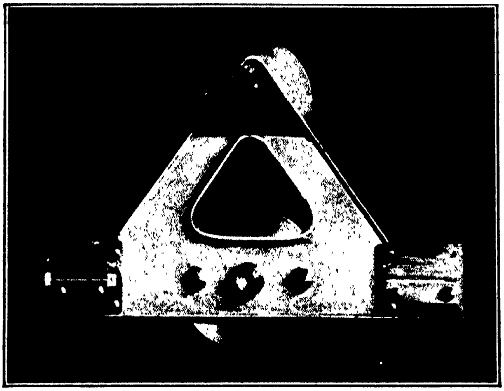


FIGURE 15

The oscillating slits. In this simple design the slit jaws are fixed in position at a width of three or four thousandths of an inch. The rectangular openings at the ends of the second (left) slit permit the H α line to be seen for adjustments when the slits are at rest.

seen on the Sun's disk when the grating aperture is reduced to $1\frac{3}{16}$ x 2 inches.* A larger grating naturally gives a brighter image, in which more detail can be seen, but the above will serve for most classes of work.

Suitable gratings, even of the smaller size just mentioned as a minimum, may not be obtainable. I have therefore tried a less expensive arrangement, which may be adopted by amateurs who wish to build their own instrument and are content (until a good grating or reflecting replica can be obtained) to see only the more conspicuous phenomena. This is a pair of 60° prisms,

* This is nearly the size of Hilger's plane grating K14, ruled with about 14,400 lines per inch at the National Physical Laboratory on a surface 3.5 x 5 cm.

which should be of very dense flint, and may be only just large enough to transmit a beam 1 inch in diameter, though a somewhat larger aperture is preferable. The dispersion of two ordinary flint prisms (here made equivalent to four by the use of a small plane mirror, which returns the light through the prisms to the second concave mirror) is less in the red than that of the first order of a (15,000) grating, and their performance is much inferior to that of a good grating; but with suitable slit-widths they will show the stronger bright and dark flocculi, as well as the prominences at the limb. If, as I greatly hope, a satisfactory method of producing cheap reflecting grating replicas of excellent definition can be found, these may ultimately become available in place of original gratings or prisms.*

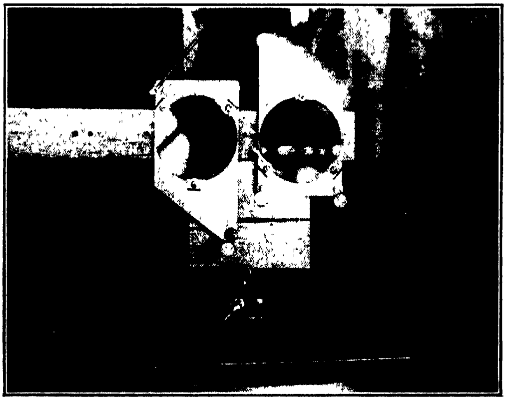


FIGURE 16

The two spherical concave mirrors of 18 feet focal length. In the finished design the left mirror is provided with a finer adjustment, to tip the mirror and thus move the H α line along the second slit to the position where it exactly follows it when in motion.

A better design for oscillating slits has recently been developed by my instrument maker, Mr. Hitchcock. In this form the slits are vertical and farther apart, and the driving mechanism is improved.

As in the case of the spectroheliograph, a monochromatic image can be produced either by motion of narrow slits with respect to the solar image, or

* The most promising means of reproducing reflecting gratings appear to be either an electrolytic process or the method described by Merfield (*Proc. Roy. Soc. Victoria*, vol. 38, 1926). The latter can perhaps be used for copying speculum metal as well as glass gratings by adopting means of preventing firm adhesion of the cathode deposit. The difficulty thus far experienced with the electrolytic method is not in securing good reproductions of the rulings, which are beautifully copied, but in obtaining replicas with plane surfaces. Those made for us have been warped several waves.

by motion of the solar image with respect to the slits. The chief difference between the two instruments lies in the fact that the spectroheliograph builds up its image gradually, slit-width by slit-width, by a slow motion of the slits or of the solar image with respect to the photographic plate, while the spectrohelioscope must reveal a considerable area of the image at once to the eye, which obviously could not see the forms of the flocculi through slowly moving slits a few thousandths of an inch wide. Hence the rapid motion of the slits or of the solar image required for the spectrohelioscope.

I have tried successfully oscillating bars carrying from one to five slits at each end and a rotating disk carrying fifty radial slits. The most effective

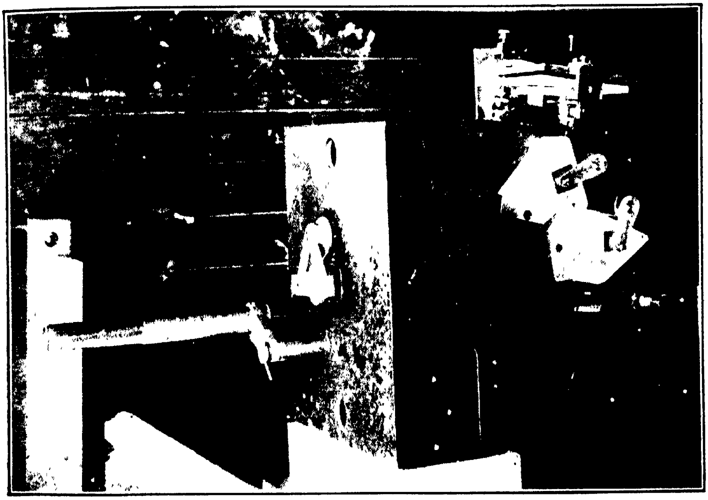


FIGURE 17

Two dense flint glass prisms and a plane mirror to double their dispersion, which can be used if no suitable grating can be obtained.

means I have tested of producing rapid motion of a portion of the solar image with respect to fixed slits is a square prism of glass mounted before each of the slits, rotating uniformly about an axis parallel to them. The portion of the solar image under observation reaches the first slit through one prism, while the resulting fixed monochromatic image is seen in an eyepiece focused through the other prism on the second slit. This ingenious device is due to Dr. J. A. Anderson. It is somewhat more expensive than the oscillating slits, and seems to show no details of the flocculi not visible with them. However, the elegance of this method, and the complete freedom from vibration and

flicker which it affords, make it an attractive alternative for oscillating slits. It can be readily attached to any Littrow spectroscope of suitable dispersion, but I have found this type of spectroscope (in which a single lens serves for both collimator and telescope) much less satisfactory for the purposes of the spectrohelioscope than the two-mirror form illustrated, because of the impossibility of excluding from the eye the light due to the illumination of the collimating lens and the grating behind it by the sunlight from the first slit. The reflected light can be excluded by using a suitable lens for the collimator, but the remaining diffuse light, superposed upon the $H\alpha$ line, materially reduces the contrast of the flocculi, even when a suitable red glass is placed over the eyepiece.

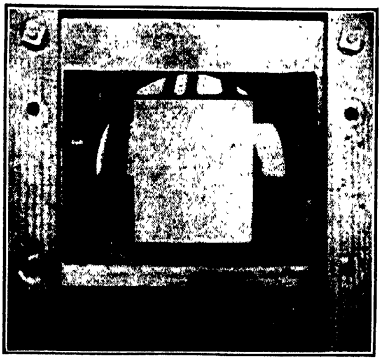


FIGURE 18

Grating seen from the north, above windows in casting corresponding to first and second slits. The plane-parallel glass plate of the line-shifter is seen from the right (second) slit. (The line-shifter, which is unnecessarily long for this instrument, was borrowed from the larger, vertical spectrohelioscope of the Solar Laboratory, described in the Scientific American, March, 1927, page 186.)

The spectrohelioscope shown in the illustrations was built from various parts that happened to be available, and does not represent the final design. The working drawings now in preparation will show a more compact support for the two concave mirrors, and various other improvements. Blueprints of these drawings, detailing all the parts of the various instruments mentioned in this paper, may soon be obtained at low cost by writing to the Mount Wilson Observatory. It should be stated whether blueprints are wanted of (A) the least expensive form of spectrohelioscope (shown in Figure 18); a more expensive form (B), with vertical adjustable slits and improved oscillating bar; or a similar design (C), provided with Anderson's rotating prisms.

In the space here available I have been unable to give many important details regarding the construction, adjustment, and use of the instruments. I hope to describe these later, partly in the *Publications of the Astronomical Society of the Pacific* and more completely in a small book on solar research for amateurs. Let me add that all those interested should read such books as Lockyer's *Contributions to Solar Physics,* Young's *The Sun,* and Abbot's *The Sun,* the latest of which is nearly up to date. Lockyer's book, published

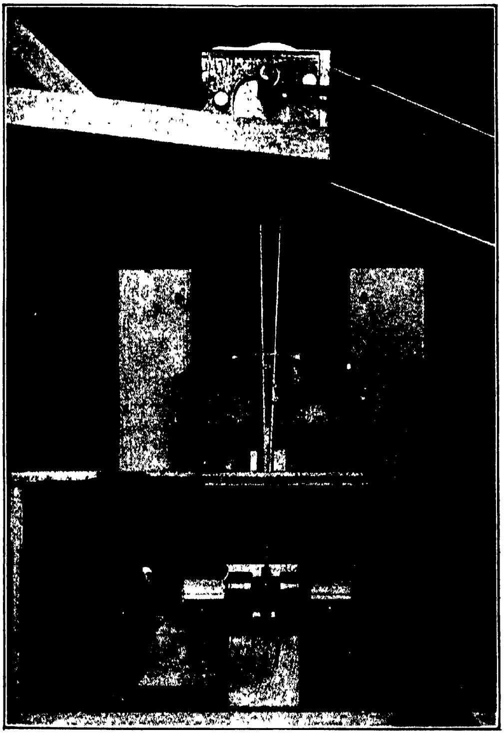


FIGURE 19

Anderson's rotating prism device for use with fixed slits. A square prism of glass rotating uniformly causes a succession of images of the Sun to move across the first slit at the rate of four per revolution. When the second slit (set on H α) is viewed through a similar prism rotating at the same rate, a stationary image is seen in hydrogen light.

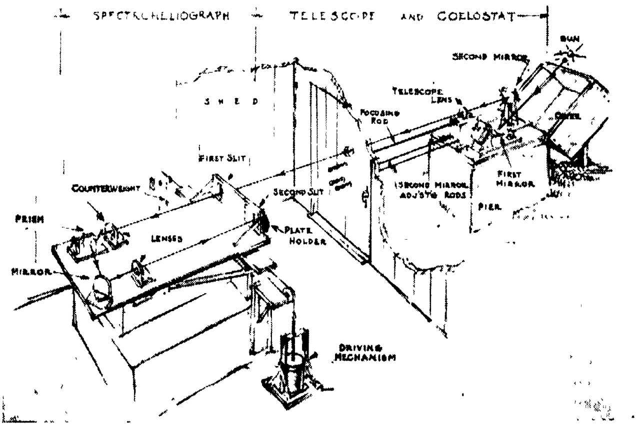
by Macmillan in 1874, contains a fascinating account of the early solar spectroscopic work and the first observations of the prominences. I have referred briefly to some of this early work in an article called "Exploring the Solar Atmosphere", published in *Scribner's Magazine* for July, 1928.

A coelostat (in which the plane of the mirror is parallel to the polar axis) is recommended in this article instead of a heliostat, chiefly because it gives a solar image which does not rotate during observation. The rotation of the image obtained with a heliostat is slow, however, and the only difficulty it involves in visual observations is the necessity of redetermining the orientation from time to time, in case the heliographic positions of the prominences or flocculi are to be recorded. The simplest possible substitute for a coelostat or two-mirror heliostat is a polar heliostat, which is merely a polar axis carrying within a fork a single mirror, which sends the sunlight upward or downward through a lens toward the north or south pole. In this case (unless a second mirror is used) the spectrohelioscope must be mounted in a plane parallel to the Earth's axis.

CHAPTER III.

A Spectroscope and Spectroheliograph—a Solar Observatory for the Amateur

Broadcasts of solar eruptions, like the more familiar radio programs, are sent out on radiations of certain wavelengths. These wavelengths are fixed by the nature of the luminous gases shot from the sun into space. Many leading astronomers, basing their opinions both on observation and theory, believe that such eruptions sometimes shower the earth's atmosphere with electrified particles which set aglow the streamers of the aurora, produce intense magnetic storms, interfere with some forms of telegraphic communi-



All drawings by Russell W. Porter

FIGURE 1

A general view of the apparatus, which constitutes a complete little solar observatory available to the average amateur.

cation and probably affect radio transmission. But the whole problem bristles with unanswered questions and thus offers splendid opportunities for research, in which amateurs with the simplest equipment may take an important part.

For those who want a still simpler and less expensive photographic outfit than the one described in the previous chapter, which can be built without the aid of machine tools, the following account of a small horizontal telescope and spectroheliograph may be of interest. In spite of the low cost, these

instruments can be used for work of great importance in its bearing on the nature of solar eruptions and their possible influence on the earth.[1]

The wavelengths used in radio communication are, of course, far too long to affect the eye. The red line of hydrogen, of much shorter wavelength, is brilliantly visible in solar eruptions. This is the wavelength chiefly used with the spectrohelioscope, where we "tune in" by rotating the grating until this hydrogen line ($H\alpha$) falls on the second slit and forms the monochromatic image we observe. At the extreme violet end of the visible solar spectrum, where the wavelength is so short that it affects the eye too feebly for visual observations, are the calcium lines known as H and K.[2] These lines are easily photographed, and our spectroheliograph must be so designed that one of them (K is the stronger) can be isolated by a narrow slit. Our purpose is therefore to make photographs of the sun with calcium light, which is more intense than any other radiation in the flocculi scattered over its surface and of exceptional brightness in the eruptions mentioned above. For this reason the spectroheliograph is our only means of recording these invisible calcium clouds in the solar atmosphere.

We must have a fixed image of the sun, given by some such coelostat telescope as that described in the papers already referred to, or by the still simpler and smaller instrument shown in Figure 2. I am indebted to Mr. Russell W. Porter for the drawings in this chapter and for his help in designing these instruments. They were built by my assistant, Mr. L. R. Hitchcock, to whom credit is due for many elements in their design.

Briefly stated, the coelostat telescope consists of three parts. The first of these is a piece of plane plate glass (C), about three inches square, selected by the method described by Mr. Porter in Part I, Ch. VIII, and mounted with its face parallel to the earth's axis. In most large coelostats this mirror (silvered on its front surface) is circular, but it is shown square in the sketch to save the necessity of cutting out a circular disk. Any glass cutter can provide such a plate, but several pieces of glass must be tested in the manner described by Mr. Porter in order to find mirror blanks with a sufficiently flat surface.

To reflect a beam of sunlight constantly upon the second mirror, the coelostat mirror must be mounted on a polar axis and rotated by a small clock movement. The polar axis, as Figure 2 shows, is a very simple affair, consisting merely of a straight steel rod (A) about 3/16 inch in diameter, attached to a square plate of brass or hard wood (B) that serves as a support for the mirror (C). A piece of sheet metal, bent in the shape shown in the drawing, is bored through its upper face to fit the polar axis, which rests against its lower face at (D). The upper end of the polar axis passes through another piece of sheet metal and carries at its extremity a pinion which engages with another pinion attached to the hour-shaft of a small brass clock movement. If the pinion on the polar axis has four times as many

[1] For accounts of these eruptions and the accompanying auroras and terrestrial magnetic storms see "Signals from the Sun," in *Scribner's Magazine* for July, 1931; and Part III in the series of my articles on the spectrohelioscope, in the *Astrophysical Journal* for June, 1931.

[2] These are the two strongest lines in Figure 7, near the center.

teeth as that on the hour-shaft of the clock, the polar axis will revolve once in 48 hours and the beam of sunlight from the coelostat mirror will be reflected in a fixed direction.

As the drawing shows, the polar axis is inclined at an angle (L) equal to the latitude of the place where it is to be used. Its two sheet brass bearings are mounted on suitable blocks of metal or wood, which are attached to a rectangular base arranged to slide north or south on the underlying support, a straight strip of wood serving as a guide. By fitting the pinion to a sleeve on the polar axis tight enough to drive by friction, but not too tight to

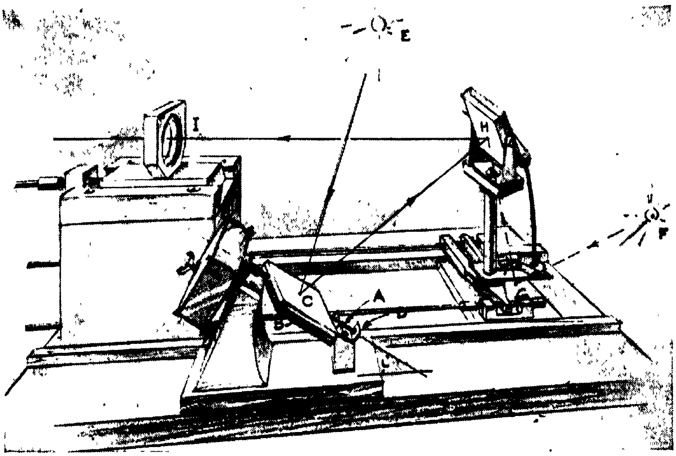


FIGURE 2

The coelostat telescope in Figure 1.

permit the axis to be turned within the sleeve, the mirror can be rotated to the proper angle to reflect the beam to the center of the second mirror, where it will be maintained by the clock.

The position of the coelostat, which may be used east or west (before or after noon) of the second mirror (H) and lens (I), depends upon the altitude of the sun, and hence upon the latitude of the site and the time of year. In the drawing, the sun (E) is shown high in the heavens, as in summer; in winter the sun is low, as indicated at F, and the first mirror must be moved south to some point near G in order to reflect the beam to the second mirror.

The second mirror, three inches square, also carefully selected for flatness and silvered on its front surface, must have two motions, both controlled from a distance. (See Figure 1.) It can be tipped about its horizontal axis

by an arm projecting down behind and ending in a fork which sits astride a curved cam. By rotating the cam-support the mirror is inclined slightly, thus causing the sun's image to move up or down the slit of the spectroheliograph. Rotation of the vertical mirror-support by means of a second rod gives a slow east or west motion of the solar image. Thus any part of the sun can be centered on the slit.

As the coelostat and second mirrors are nearly plane surfaces, they serve only to reflect a parallel beam of sunlight constantly in a horizontal line to the north. The telescope proper consists merely of a single plano-convex lens (I) about one or two inches in diameter, of from 9 to 18 feet focal length, depending upon the size of the solar image desired. A lens of 18 feet focal length will give a solar image about two inches in diameter, the size of the original photograph from which Figure 8 is reproduced. This is too large to be photographed as a whole by this spectroheliograph, but as most of the calcium flocculi are confined within two zones covering a moderate range in solar latitude, and as the more important eruptive phenomena (for our purpose) usually occur not far from the center of the sun, a two-inch image can be used if it is desired to show the smaller flocculi on a larger scale than a shorter focal length would give. However, a one-inch image, given by a lens of nine feet focal length, may be used if preferred.

Perhaps it should be added that a single lens, even of this small aperture, cannot be expected to show very sharp details in white light, though sun-spots may be seen with it. If of fairly good figure it serves perfectly, however, for the photography of objects like the flocculi with light of a single wavelength, because there is no overlapping of the countless images formed at increasing distances from the lens by light ranging from violet to red.

It is evident that when the calcium flocculi are to be photographed the violet image corresponding to the K line of calcium must be focused on the first slit of the spectroheliograph by the method described below. For this purpose a focusing screw, with rod reaching to a point near the spectroheliograph, is provided. As for the telescope lens itself, it may be mounted in a wooden[3] support (with the convex surface toward the second mirror), attached to a sliding block, as shown in Figure 2.

The coelostat telescope should stand in the open air on a pier about three feet high, as illustrated in Figure 1. To protect it from the weather a waterproof wooden box, arranged to lift off or to turn out of the way on hinges, may be used. A heavy box rammed full of earth will serve very well for a pier, though a concrete pier, on a wider concrete base "floated" on sand to absorb vibrations, is preferable. The spectroheliograph, which must now be described, stands in a small shed to the north, at a distance fixed by the focal length of the telescope lens.

Figure 3, which shows the optical parts of the spectroheliograph, should serve to make its operation clear. The image of the sun, entering the shed through an opening, falls on the slit S_1, seen here (and in Figure 4) from the inside, and in Figure 5 from the outside. The diverging beam of white

[3] All parts made of wood may be prevented from warping by soaking the wood in hot melted paraffin until its pores are saturated.

light then meets the plano-convex spectacle lens L_1, about $1\frac{1}{2}$ inches in diameter and of 15 inches focal length, mounted with its convex face toward the prism P. As the lens is supposed to be set at a distance from the slit equal to its focal length (for the violet light of the K line), a parallel beam emerges from it, and is dispersed by the prism. The short diffuse spectrum thus formed falls upon the mirror M_1, a square or circular piece of selected plate glass, silvered on its front surface. This sends the dispersed light to the lens L_2, which is exactly similar to L_1, and is mounted on the same support, so that both can be moved together toward or from the slits for focus-

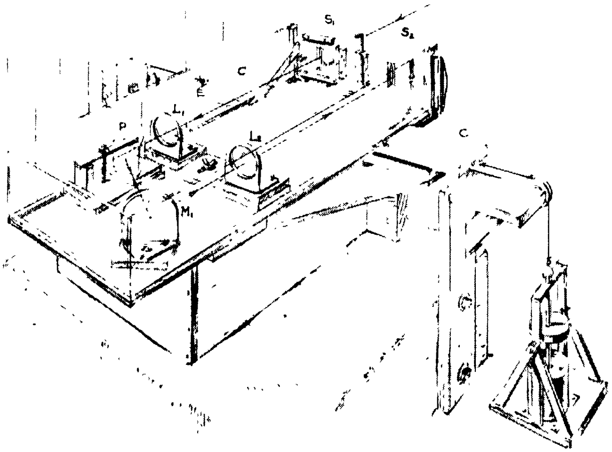


FIGURE 3

The spectroheliograph in Figure 1.

ing. A distinct image of the spectrum is thus formed on the brass plate, hinged at one end, that carries the second slit S_2. When this plate bearing the second slit is swung out of the way, the spectrum falls upon a photographic plate held in a plate-holder mounted at a fixed position beyond it. In this way, with the whole apparatus at rest, photographs of the solar spectrum can be taken.

Before describing the adjustments in detail, let us see how the instrument is used. All of the parts enumerated above, excepting the support for the fixed photographic plate-holder, are fastened to a flat plate, which may be of three-ply wood, stiffened by the wooden sides and ends (shown here as transparent for clearness) of the enclosing box that excludes extraneous light, but more advantageously of metal. Under this box, near the slit end, is the

blue. Then a second series of exposures, between which the lenses are moved about one eighth of an inch each time, will quickly bring these strong lines into sharp focus on the plate. With the aid of a pair of dividers the radius of curvature of the K line can be determined and the jaws of the second slit S_2 formed to fit the line. It should be added that these jaws are bevelled on the *outside* (toward the photographic plate), so as to present a plane blackened face to the incoming spectrum and thus prevent reflections.[6]

As the K line is practically invisible, the problem of setting it on the second slit remains. The two jaws of the second slit are fixed in position, at a distance apart of about 0.003 inch. To the right, (toward the first slit, Figure 5) is a small rectangular window (A) in the brass plate that carries the second slit, through which the violet region of the spectrum can be seen.

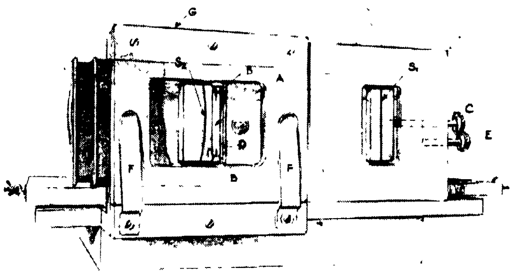


FIGURE 5

Slits and plate holder, from the south.

The line selected for setting is the iron line λ 4325.9, (Figure 7), in my instrument about nine sixteenths of an inch to the right of K. This distance is accurately measured on a photograph of the solar spectrum, where λ 4325.9 and K are practically at the same focus. A pair of small wire pointers (B, B, Figure 5), (pieces of wire bent to a right angle), attached to the upper and lower ends of the right-hand slit-jaw and projecting to the right just far enough to place their vertical tips at the correct distance from K, are observed through a magnifier. The first slit is moved as a whole by the screw (E) and the spectrum moves with it. When the two pointers coincide with the line λ 4325.9 the K line must be on the second slit, assuming the measurements and adjustments to be correct. A small brass plate (D, Figure 5), moving easily and made to slip under a groove at the base of the right slit-jaw, is then slid over the window to exclude from the plate all light except that of the K line, which now passes through the second slit.

[6] A straight first slit and curved second slit necessarily mean a distorted solar image; A circular image can be obtained by giving each slit half the curvature (twice the radius) found as above for the second slit.

Focus of solar image: The solar image must now be focused on the first slit for calcium (K) light. Look at the image on a white card held against the slit-jaws through a piece of red or yellow glass, and focus the lens of the coelostat telescope until it appears sharply defined. Then move the sun's image until its lower edge is at the middle of the first slit, which should be radial to the disk. Look at the upper edge of the spectrum with a magnifier, and focus the coelostat lens (by moving it north) until this edge appears sharp in the violet. Proceed from this point photographically, moving the

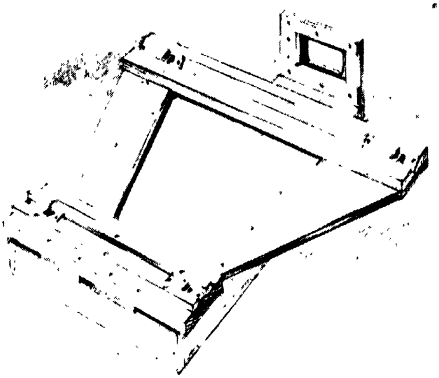


FIGURE 6

Base plate to carry spectroheliograph.

lens north about one fourth of an inch between exposures, until an image of the spectrum is obtained which is sharp on this edge at the position of the K line.

Plate-holder: In order to keep the plate as close as possible to the jaws of the second slit, a thin plate-holder is needed. A very good one for this purpose is of light sheet metal and takes a plate about 2¾ by 4¼ inches. This is mounted in a wooden support (G, Figure 5) which holds it in contact with a piece of felt cemented to the brass plate that carried the second slit, but cut away opposite the slit-jaws over an area large enough to transmit the images of the spectrum and the sun. The pressure of the springs (F, F, Figure 5) that hold the plate-holder against the felt must not be great enough to interfere with the smooth and uniform motion of the driving mechanism.

Driving mechanism: It is not as easy as one might suppose to produce perfectly uniform motion. The spectroheliograph, because of the narrow slit before the photographic plate, has an uncanny way of showing any irregularities, which appear as lines or bands across the monochromatic image

of the sun. After using many driving devices at the Kenwood, Yerkes, and Mount Wilson Observatories, I recommend for the present instrument an extremely simple hydraulic arrangement similar to that employed in my earliest work with the spectroheliograph 40 years ago. It consists of a vertical cylinder (Figure 3), in its simplest form merely a circular brass tube about 8½ inches in diameter and 4½ inches high. In this a piston of lead

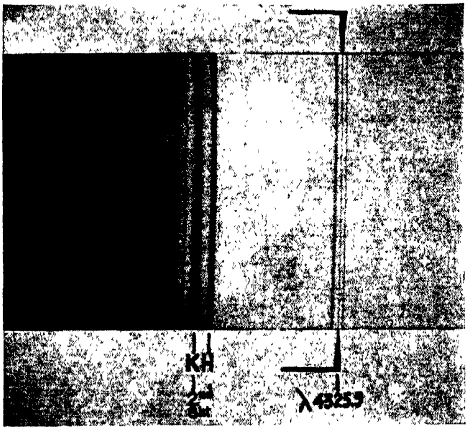


FIGURE 7

The violet end of the spectrum, showing ultra-violet region to the left, strong H and K lines (center) at the limit of the visible region, and iron line at wavelength 4325.9 angstrom units, on which the pointers are set when the calcium line K is on the second slit. (This line is the one to the left of the pointers.) Enlarged nearly three diameters from original negative.

slides easily. A piston rod, passing loosely through a hole in a bar above it, carries the lead driving weights and serves as a guide and as a means of communicating motion to the spectroheliograph by the aid of a thin steel tape or wire. The cylinder is nearly filled with liquid, which may be a thin oil or a half-and-half mixture of glycerine and water, which will not freeze. A counterweight, hanging from a pulley on the opposite side of the spectroheliograph, keeps the tape taut. The speed is regulated by three holes in the piston, which can be varied in size to vary the rate of flow. This rough contrivance served to give the photograph reproduced in Figure 8. A more perfectly made arrangement of the same kind would give smoother motion.

With the apparatus described above a great variety of experiments can be made. When clamped in a fixed position it serves very well as a spectroscope, with which much of the visible, ultraviolet, and infra-red spectrum can be photographed on plates sensitive to these regions. Many of the experi-

ments described in books on spectroscopy can be easily performed, as it is a simple matter to make the auxiliary apparatus required for producing the spectra of flames, arcs, and sparks, while vacuum tubes containing hydrogen, helium, and other gases are not expensive. The solar spectrum, as already stated, can be photographed, and the presence in the sun of sodium, magnesium, calcium, iron, and many other elements proved by photographing their spectra on the same plate beside it. By holding the sun's image exactly tangent to the slit during an exposure, the bright lines of calcium, hydrogen, and helium can be photographed in the chromosphere, which surrounds the sun as a sea of glowing gas. These lines reach to higher levels in the prominences, the forms of which may be registered by using the instrument as a spectroheliograph and giving an exposure, with the *K* line set on the second slit, longer than that required for the sun's disk. In work of this kind the

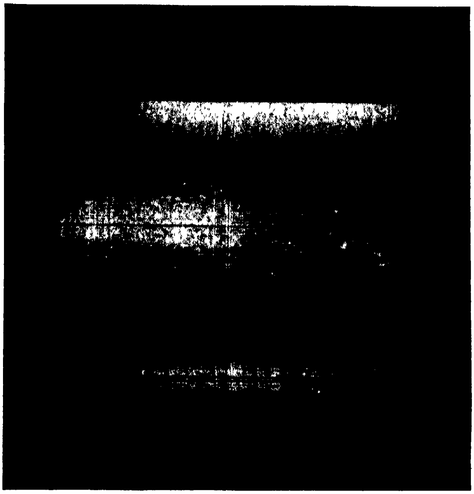


FIGURE 8

Photograph of the sun, showing calcium flocculi and bipolar sun-spot (near right edge).

clock must keep the sun perfectly stationary, and the direct light of the brilliant disk should be excluded by a circular metallic screen, slightly larger than the solar image, fixed in position before the first slit.

It is easier to record the bright *H* and *K* lines in the spectra of the flocculi, which are scattered irregularly over the sun, as shown by Figure 8. For this purpose the instrument is fixed in position while the spectra of

various parts of the disk (especially near sun-spots) are photographed with exposures shorter than those needed for the prominences. Narrow bright lines will be seen on the photographs with a magnifier at the center of the broad dark *H* and *K* lines, at points where the first slit happens to cross calcium flocculi. The occasional eruptions on the sun's disk described in the articles referred to are represented by exceptionally bright calcium flocculi, which appear suddenly, change rapidly in form and area, and last from a few minutes to two or three hours.

The advantage of using calcium light is most easily recognized by taking a photograph of the sun with the same instrument, after moving the first slit a short distance so as to bring a part of the spectrum outside of the *K* line upon the second slit. In this case the calcium flocculi will not be recorded and only the sun-spots, perhaps with some faculae near the edges of the disk, will appear.[7]

[7] Readers who wish to know more about the calcium flocculi may consult such books as Abbot's "The Sun" or Russell, Dugan and Stewart's "Astronomy."

Part X.

CONTRIBUTIONS BY ADVANCED AMATEURS

CHAPTER I.

The Compound Telescope—Cassegrainian and Gregorian Types

By JOHN H. HINDLE, F.R.A.S.
Member of the British Astronomical Association; Vice-president of the Manchester Astronomical Society, Governing Director, Union Engineering Works.

The ordinary, or Newtonian type of reflector consists essentially of a paraboloidal mirror, which converges a parallel bundle of rays into a cone, at the apex of which an eyepiece is placed to magnify the image. The magnifying power available depends entirely on two factors—the focal lengths of the mirror and eyepiece, respectively.

Thus the precise magnifying power is Fm/Fe, where Fm is the focal length of the mirror and Fe that of the eyepiece. This latter, the divisor, cannot be reduced indefinitely, so that if a high magnification is required Fm must be increased. This immediately involves a longer tube, and a greater distance to climb in order to follow the eyepiece.

It is possible, fortunately, to utilize a comparatively short cone, and so modify the point of the cone, either by refraction or reflection, that we get the effect of a very much longer cone. The so-called Barlow lens cuts off a portion of the summit of the normal cone, and substitutes another and longer summit, having a sharper angle, the apex $f2$ of which is in turn examined by an eyepiece. Strictly speaking, the Barlow lens should be an achromatic combination if the best results are to be obtained. See Figure 1.

The relation between the two cones, and the apparent or "equivalent" focal length of the mirror or object glass when thus amplified, is simply determined thus: The length of the *new cone formed* is divided by the length of the normal cone *cut off*. This ratio is the amplifying power A by which the normal focal length of the mirror or object glass is to be multiplied.

To produce the required effect by reflection, a small secondary mirror is used in conjunction with the paraboloidal mirror. This latter has a central hole through which the newly formed cone of rays passes to the eyepiece, so that there are only two reflections in all, as in the Newtonian. Such a combination may properly be termed a compound reflector, because the focal length of the large mirror is very considerably increased by the second reflection.

We may, for the purpose indicated, either use a small *convex* mirror *inside* the principal focus (known as the Cassegrain system) or we may use a small *concave* mirror *outside* the principal focus (known as the Gregorian system). In both cases, the radius of curvature of the secondary mirrors is calculated to throw the image through the hole in the large mirror, and a convenient

distance behind. In both systems the secondary mirrors have to be figured in order to focus correctly, and the principal object of this contribution is to describe new workshop methods of ascertaining and correcting the contour of the secondary mirrors with the greatest possible degree of accuracy.

In company with the refractor and the Newtonian, the Cassegrain gives an inverted image. The Gregorian, on the other hand provides an erect image, perhaps not quite so acceptable to the astronomical observer, but one that should, after all, present no difficulty from a visual or photographic point of view.

Figure 2 is a comparison of the Cassegrain and Gregorian systems, to the same scale. Adopting Professor Ritchey's nomenclature for the Cassegrain, we designate the portion of the old cone cut off, p, and the new cone formed p'. These distances are indicated for both systems in Figure 2. As previously stated, in both cases, p' divided by p, equals A, the amplifying power, or ratio, by which the focal length of the large mirror is multiplied.

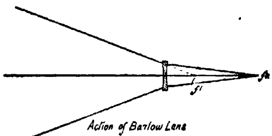


Fig. 1

All drawings by the author

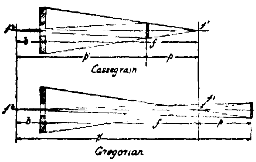


Fig. 2

If the focal length f of the large mirror is decided upon, the amplifying power A, and the position of the secondary focus behind the large mirror at a distance b, then we obtain the position of the secondary mirror as follows:

$$\text{Cassegrain } p = \frac{f \text{ plus } b}{A \text{ plus } 1} \qquad \text{Gregorian } p = \frac{f \text{ plus } b}{A \text{ minus } 1}$$

and p' follows as a matter of course.

The radius of curvature RC of the secondary mirrors in each case is determined as follows:

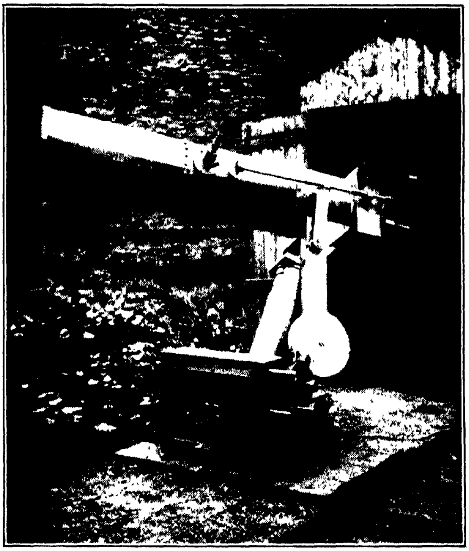
$$\text{Cassegrain } RC = \frac{2\,p'\,p}{p' \text{ minus } p} \qquad \text{Gregorian } RC = \frac{2\,p'\,p}{p' \text{ plus } p}$$

The diameter of the secondary mirrors is limited by the obstruction they cause to the light falling upon the large mirror and this consideration fixes a *minimum* value for A, which may be assumed at 3 for the Cassegrain and 5 for the Gregorian. In any case the diameter should be slightly greater than mere geometry indicates, which is

$$\frac{\text{diameter of large mirror}}{\text{focal length of large mirror}} \times p$$

At least another half inch should be allowed and, by the methods indicated later, this additional surface can be as accurately figured as the remainder.

It is important to notice that the amplifying power of the Gregorian is, other things being equal, greater than that of the Cassegrain. Thus, for equal diameters of secondary mirrors, if the amplifying power of the Cassegrain



The 12 inch Newtonian-Cassegrainian-Gregorian telescope made by the author and used as the basis for the example of calculations given in this chapter. It has a novel type of mounting which permits free access to the secondary focus. The counterweight is double and is cast in one piece, shaped like the letter "U." There are differential screws for declination The drive is a synchronous motor with cord-operated hand adjustment in R.A.

is X, then that of the Gregorian is X plus 2, and the mirrors will be farther apart in the latter case by the distance $2p$.

The following calculations show how the foregoing formulae are applied to a Newtonian-Cassegrain-Gregorian combination. The preliminary assumptions are: the diameter and focal length of the large mirror, the position of the secondary focus behind the large mirror (b in Figure 2), also the amplifying power, which is chosen so that the secondary mirrors are not too large. The assumptions are:

Diameter of large mirror		12 inches
Focal length, f	60 inches	$f/5$
Cassegrain amplifying ratio	4	$f/20$
Gregorian amplifying ratio	6	$f/30$
Secondary focus behind large mirror		15 inches

The position of the secondary mirror is as follows:

$$\text{Cassegrain } p = \frac{60 \text{ plus } 15}{4 \text{ plus } 1} = \frac{75}{5} = 15'' \text{ and } p' = 4p = 60''$$

$$RC \text{ of convex} = \frac{2 \times 60 \times 15}{60 - 15} = 40''$$

$$\text{Minimum diam.} \frac{12}{60} \times 15 = 3 \text{ or, say, } 3\tfrac{1}{2}''$$

$$\text{Distance between mirrors} = f - p = 60 - 15 = 45''$$

$$\text{Gregorian p} = \frac{60 \text{ plus } 15}{6 \text{ minus } 1} = \frac{75}{5} = 15'' \text{ and } p' = 6p = 90''$$

$$RC \text{ of concave} = \frac{2 \times 90 \times 15}{90 \text{ plus } 15} = \frac{180}{7} = 26'', \text{ nearly}$$

$$\text{Minimum diam.} = \frac{12}{60} \times 15 = 3, \text{ say } 3\tfrac{1}{2}''$$

$$\text{Distance between mirrors} = p' - p = 90 - 15 = 75''$$

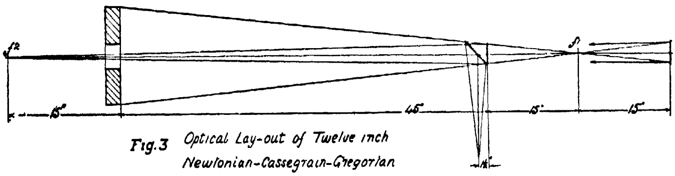


Fig. 3 Optical Lay-out of Twelve inch Newtonian-Cassegrain-Gregorian

For constructional reasons, the elliptical flat for the Newtonian will be slightly nearer the primary mirror than the convex. A figured and dimensioned diagram of the optical layout is in Figure 3.

Grinding and Polishing

The processes of grinding and polishing are very adequately described elsewhere. It simply remains to emphasize a few points which require special attention.

It is very desirable that the primary and secondary mirrors should be truly edged and of equal substance or thickness throughout. They may then be accurately fitted in their respective cells, without fear of distortion.

The larger mirror should be *partially* perforated before fine grinding, using a thin metal tube not more than 3″ outside diameter, and penetrating three-quarters the way through or slightly more. The annular groove is then cleaned out and filled with melted beeswax. This enables the fine grinding, polishing and figuring of the mirror to proceed in the ordinary manner. When we are certain that the figure is correct or as good as we can make it, the same metal tube is again run into the slot with the addition of a very little fine Carborundum and water and the final perforation made.

The radius of curvature of the concave mirrors can be tested by spherometer or by reflection from the fine-ground wetted surface. The accuracy of the convex can be tested by similarly measuring the concavity of the glass on which it is ground.

The grinding and polishing of the secondary mirrors, convex or concave, requires special consideration. Their small size makes grinding and polishing by hand a comparatively easy task. The figuring presents difficulties which make machine polishing preferable, and it is therefore worth while to rely on

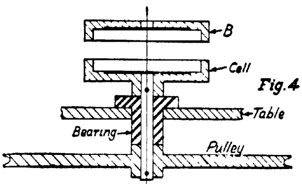


Fig. 4

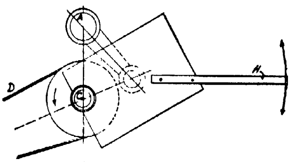


Fig. 5

the machine throughout. An ordinary sensitive drilling machine is ideal for the purpose, with the addition of a few devices for obtaining the variety of motion desirable.

We first require a revolving cell or disk which will hold either the mirror, the grinder, or the polisher. This with its shaft and driving pulley is shown in Figure 4. The table is swiveled through the angle *A* in Figure 5, so that the drill spindle comes exactly over the center of the mirror cell at *C*, and which is rotated by the driving cord *D*, side throw being introduced by hand at the handle *H*. We also require another cell to hold the grinder or polisher, as shown at *B*, Figure 4. This is a replica of the rotating cell, with a 3/8″ hole through the back.

We next require a complete set of drivers, for providing the requisite composite motion of the upper cell. These drivers are shown in Figure 6, and have a radius of rotation of 1, 2, 3, 4, 5 and 6 eighths of an inch. We also provide a perfectly straight one for the purpose of grinding a small spot in the precise center of the face of each secondary mirror for collimation purposes later on. The drivers are all bent from quarter inch round steel rod, and each should be marked distinctly so that we can correlate cause and effect when figuring.

Our machine therefore imparts a quasi-circular motion of the upper cell, while the lower cell rotates slowly and can simultaneously be swung from side to side by the handle. Usually three speeds of the drill spindle are available—100, 200, and 400 r.p.m. The rotating cell may run from 10 to 20 r.p.m.

When the mirror is sufficiently fine-ground, the polisher may be made on the glass grinder. We are then in a position to have either the polisher or the mirror on top and, as these two methods of polishing produce entirely different effects, we have, along with the varied throw from the drivers, numerous combinations to enable the desired figure to be arrived at.

Testing the Paraboloid

The large mirror is to be figured to a parabolic curve as exactly as possible. The knife-edge testing apparatus must therefore have stability, no backlash, and facilities for reading to 0.001 inch. The zonal apertures should be cut in sheet metal, which can be rigidly fixed in front of and close to the mirror, in correct alignment. An additional diaphragm with the zonal apertures staggered around the periphery is arranged to rotate freely on

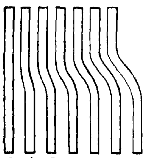


Fig. 6

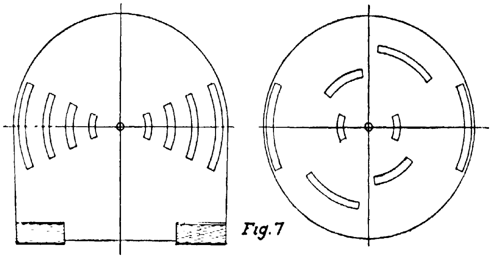


Fig. 7

its center, and expose each zone in turn. Figure 7. It is no disadvantage if the outer and inner zones are exposed simultaneously, so that an "overall" reading can be taken. If the curve is a smooth one (which it will be if correct methods of figuring are adopted) it is merely a waste of time to read the intermediate zones until the total aberration is about correct.

Taking as an example the 12-inch mirror of 5-foot focal length previously referred to, we may use 4 zones $^3/_8$ inches wide. The aberration is calculated as follows:

	Mean r of Zone	r^2	$r^2/120$	Difference
0	5.70	32.49	0.270	
1	4.40	19.36	0.161	0.109
2	3.10	9.61	0.080	0.081
3	1.80	3.24	0.027	0.053

If we focus on the outer zone, the knife-edge is to be moved nearer the mirror for each successive zone. Calling the outer zone zero, the second zone should require a movement of .109 inches, the third zone a further movement of .081 inches and the inner zone, an additional .053 inches. If we test directly from the outer zone to the inner zone, then the knife-edge should move .270—.027=.243 inches.

There is another method of testing the total aberration as a preliminary measure. Without diaphragms, the knife-edge is carefully focused on the extreme edge of the mirror. It is then advanced until the precise center is in focus. Both of these positions can be very accurately obtained with a little practice, and the difference should be r^2 divided by R, or substituting, 6^2 divided by 120 equals .3″, rather more than from outer to inner zones, of course. The arrangements for correcting the secondary mirrors assume the large mirror to be a perfect paraboloid, but we must take particular care not to overcorrect it.

Testing the Secondary Mirrors

The method of testing a Cassegrain by means of a large plane mirror and parallel rays is illustrated in Professor Ritchey's description, and is reproduced with a perforated mirror. It demands a plane mirror the same size as the great mirror. As is well known, the plane mirror first requires a spherical mirror of the same aperture, and its production is an arduous undertaking for an amateur. Not only is there possibility of accumulated error in the plane mirror, but the test presents serious difficulties. For example, unless the illuminated pinhole is exactly on the axis, the passage of rays to and fro over a comparatively long path, no less than 6 times (5 reflections) and the consequent accumulated deflection, distorts the apparent figure of the convex. This effect is intensified if the mirrors are not in absolutely perfect alignment. In addition, the surface of the convex visible for correction is one corresponding to point illumination only, and there is always a suspicion that gross inaccuracies exist just outside the visible area.

A far superior method of testing secondary mirrors, either Cassegrain or Gregorian, is the remarkably simple one of using a spherical mirror in place of the paraboloidal mirror used in Ritchey's test, thus eliminating the plane mirror entirely and dispensing with the parallel rays. See Figure 8, taken from *Monthly Notices of the Royal Astronomical Society*. (This paper is reproduced at the end of the present paper, for reference.) In this arrangement there are only three reflections, two being from the secondary mirror, whose imperfections stand out in extraordinary relief. The only precautions required in setting up the two mirrors are that they must be approximately the correct distance apart and squarely facing each other. The precise radius of curvature of the spherical mirror is *not important*. If it is slightly larger than the paraboloidal mirror, then the radius of curvature may equal the focal length. If it is the same size, the radius of curvature may be shorter so as to expose the whole of the convex surface for correction. Again, the hole in the test mirror need not be larger than amply sufficient to view the

full aperture of the convex from the secondary focus. The spherical test mirror is silvered in advance and it is better to silver the secondary mirror for the preliminary set-up, so that precise collimation can be obtained by reflection, the secondary mirror to be removed and replaced without disturbing correct alignment. The test then becomes as simple as that of a spherical mirror at the center of curvature, but more rigorous, so far as the secondary is concerned, on account of the double reflection; moreover, there is no obstruction from the supports of the secondary mirror, which we see in its entirety with the comparatively small black spot in its center.

It has long been acknowledged by all competent authorities that the production of the paraboloidal mirror in the workshop, properly and fully corrected by the zonal method, leaves nothing to be desired, and no sky-tests can suggest any practical improvement. Here, then, is a method of testing the secondary mirrors with even a greater degree of accuracy, and without reference to the paraboloidal mirror in conjunction with which they are to work. The happy-go-lucky methods of producing secondary mirrors formerly in vogue—in some cases making half a dozen and selecting the best after a trial on the sky—need no longer be resorted to.

For the secondary mirrors in our 12-inch combination telescope, we therefore require a spherical mirror 10″ to 14″ in diameter, of 50″ to 60″ radius of curvature, with 1½″ hole. Such mirrors are not difficult to produce and their intense curvature prevents serious deviations from the sphere when polishing.

When we test our secondary mirrors by the method indicated we see the complete mirror brightly illuminated and standing out in strong relief. Assuming they are spherical, we find the apparent section of the solid represented in Figure 9, *A* and *B*, for the Cassegrain and Gregorian respectively. In both instances, with stationary pinhole, there is usually a difference of focus as tested by the knife-edge of a couple of inches between minimum and

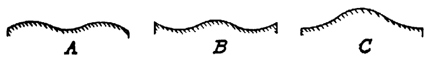


Fig. 9

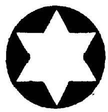


Fig. 10

maximum. If the image of the pinhole is examined by an eyepiece the dispersion of light is seen to be very considerable and along the lines of aberration usually two more or less distinct images of the pinhole are found, the one having the shorter focus being smaller and fainter, with a surrounding haze. When the mirror is corrected so as to appear perfectly flat, the eyepiece focus is well defined in position and there is no stray light exterior to the pinhole. The image of the pinhole expands in a similar manner on both sides of focus; in fact, if the secondary mirror is correctly figured, the appearances are exactly those of a spherical mirror under a similar test at center of curvature.

Practical Methods of Figuring Secondary Mirrors

If we examine the apparent shape of the Cassegrain convex under test, it is obvious that the middle zone has to be polished away. This means actually a depressed intermediate zone on the spheroidal convex, hence the necessity for a quasi-circular motion. Under a straight stroke, the depressed zone would soon disappear and the curve become spherical again. It also makes a wonderful difference to transpose the position of mirror and polisher. The convex mirror should, generally speaking, be polished with the polisher on top, using the 1/8″ or 1/2″ driver, and simultaneously swinging the table so that the polisher overhangs well first one side then the other. This produces a spherical surface free from rings; as we may reasonably assume under test from the intensity and regularity of the apparent solid produced. If we place the mirror on top and increase the stroke, say to the 1/2″ driver with only sufficient side throw to avoid grooving, we immediately begin to wear away the intermediate zone, and the mirror assumes a more flat appearance. This is explained by the overhang of the mirror relative to the polisher.

The raised intermediate zone can also be rapidly reduced by using on top a polisher about 2/3 full size, a star being cut out of the center, the points of the star reaching the periphery of the polisher. Figure 10. This is a most effective tool for figuring a convex surface. The driver is chosen so that the circular stroke carries the polisher all around the edge of the mirror, taking nothing at the edge and a maximum at the intermediate zone. The excavated, serrated center of the polisher reduces the cutting action in the very center of the mirror again to zero, and blends the surface well. Two or three metal blanks, say 1/2, 2/3, and 3/4 size, may be used experimentally in this way in order to find which, in combination with the proper driver, produces the best effect. The final process may well be to run the mirror a little while on top of the full sized polisher, as before indicated, so as to eliminate any astigmatism which is sometimes introduced, particularly if we over-correct the mirror in the first instance and then afterward reduce it. Under such circumstances the astigmatism is plainly visible and it is better to polish back to the sphere and figure again.

The figuring of the Gregorian secondary mirror is a much simpler problem because there is no under-cutting, as in the convex. If we shorten our focus slightly when testing the concave with the spherical mirror we get a surface like Figure 9C. All that is necessary is to excavate most in the center, graduating to nothing at the edge, to make the concave mirror look perfectly flat. By the time the amateur has achieved these results with the aid of the spherical mirror he will not be surprised at the lack of enthusiasm with regard to Cassegrain and Gregorian reflectors in the past. There is, however, now no reason why their use should not be very considerably extended.

It has been stated that, in compound reflectors, the mirrors can be sympathetically figured to cancel out serious defects. This is a somewhat exaggerated statement, as anyone who completes the figuring of the mirrors described in this article will be prepared to contend. For instance, there is, in the first place, no possible deviation from the paraboloid for the large mirror

which will render the figuring of the small mirrors any easier. The reverse is probably the truth and a perfectly smooth curve and full correction are obviously essential in the paraboloid. The following conditions obtain:

1. If the secondary mirror is perfectly corrected and the large mirror under or over-corrected, the secondary mirror simply reproduces, in an augmented fashion, the characteristics of the large one. Particularly note:—

2. If the large mirror is correct and the secondary *under*-corrected, then the combination shows *over*-correction, in a Cassegrain.

3. Similarly, if the secondary is over-corrected, the combination shows *under*-correction, in a Cassegrain.

Taking into account the possible combinations of imperfectly corrected large and small mirrors, a haphazard pair which under these circumstances gave even normal results would be a most fortuitous combination, seeing that means for rigorous testing have hitherto been wanting.

All we may say, even with the assistance of this rigorous test, is that if the large mirror is slightly under-corrected, then the secondary mirror may be likewise, and vice versa. The amount of under-correction and over-correction must of course be estimated by eye alone and would consist in leaving the secondary mirror not quite flat or, on the other hand, taking it a little beyond perfect flatness.

Adjustments in the Telescope

After experience with the new method of testing the secondary mirrors it will be realized how important it is that the alignment or collimation of the mirrors should be perfect in the telescope, otherwise the useful effect of figuring is almost entirely thrown away and an astigmatic image results.

Assuming that the large mirror is adjusted to look centrally out of the tube, the convex mirror is placed in position and the reflection of the large mirror made to look central from the eye end. Outside this reflection of the mirror there will also be a black annular ring—the reflection of the inside of the tube. This annular ring should be symmetrical and of equal thickness all around; this is the first adjustment to be made to the convex itself. We then look for the reflection of this reflection in the convex, another and a smaller black annular ring. This is brought concentric by tilting the large mirror slightly. Both black rings should finally be perfectly concentric with each other and with the central ground spot denoting the geometrical center of the secondary mirror.

It is not necessary nor desirable to make the secondary mirrors adjustable longitudinally by screw. That would merely vitiate the delicate adjustment. Provision for permanent adjustment, such as tilting the cell in any required direction, moving it laterally across the tube, or advancing it backward or forward so as to bring the focus to the correct position, is absolutely essential. Figure 11.

Eyepieces suitable for each combination should be selected. For the Newtonian equivalent focal lengths of .50″, .35″, and .20″ are suitable. Messrs. Cooke, Troughton & Simms, Limited, make a special orthoscopic eyepiece

especially designed for short focus reflectors, consisting of a triple combination of little power, which is very over-corrected for color and aberration. The eyepiece is a powerful simple lens, the aberrations of which are completely neutralized by the triple combination. This arrangement allows very perfect corrections and unusual eye clearance.

Ordinary eyepieces of 1", 1½", and 2" *f.l.* are suitable for the compound reflectors, but the eye lens should be covered with an eye plate perforated

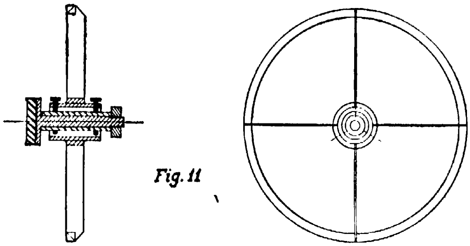


Fig. 11

the exact diameter of the Ramsden disk. The diameter of this disk may be actually measured, or arrived at as follows: If diameter of primary mirror $= D$, *e.f.l.* of compound reflector $= fD$, and focal length of eyepiece $= fe$, then the magnifying power $p = fD/fe$, and the diameter of the Ramsden disk $= D/p$.

It is advisable to have the eyepiece mount at the secondary focus adjustable on three screws, so as to bring the Ramsden disk precisely in the center of the hole in the eyeplate for the very finest performance.

—Union Engineering Works, Witton, Blackburn, Lancashire, England.

[Editor's Note: Mr. Hindle's paper, "A New Test for Cassegrainian and Gregorian Secondary Mirrors," first published in the *Monthly Notices of the Royal Astronomical Society*, March, 1931, is reprinted below by permission.]

1. The figuring of the secondary mirrors for compound reflectors has always been considered a difficult problem. The comparatively recent revival of the Cassegrain is undoubtedly due to the "parallel ray" system of testing adopted by Professor Ritchey, and illustrated and described on page 39 of his work "The Modern Reflecting Telescope." It may be noted that the concave secondary mirror for a Gregorian can equally well be tested by the same method.

2. That test leaves much to be desired. No matter how carefully the mirrors are collimated, the convex does not appear as a perfect surface of revolution, when examined under the knife-edge, probably because the illuminated pinhole and the eye cannot simultaneously be on the optical axis. There is a large blind spot in the center of the convex, due to its interposition in the parallel rays returning from the plane mirror. The area visible

is that due to point illumination only. The supports for the convex obstruct the view to some extent, in addition to which there are diffraction effects around all obstructions. The plane mirror used must be at least as large as the paraboloid, and requires first a spherical mirror from which it is derived with diminished accuracy. The five reflections are objectionable; to a certain extent they drown that figure of the secondary mirror which we wish to see.

3. By the remarkably simple device of substituting a slightly larger *spherical* mirror in place of the *paraboloid*, with the radius of curvature approximately equal to the focal length of the latter, we immediately *dispense with the parallel rays, and reduce the number of reflections to three.* The secondary mirror is then seen under the shadow test in no uncertain manner.

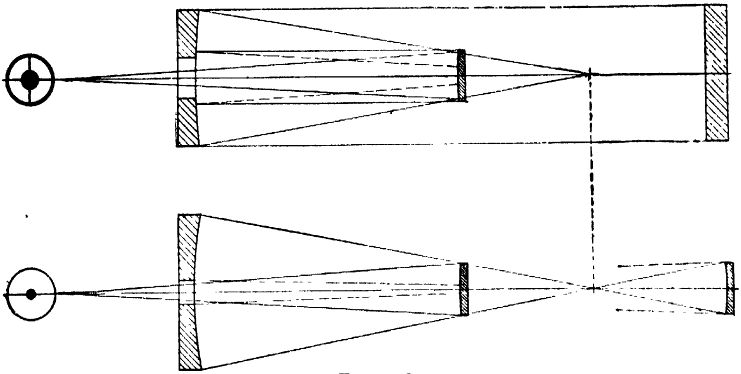


FIGURE 8

It can be correctly figured over a larger diameter. The blind spot in the center is much smaller, and the supports for the secondary mirror do not obstruct the view. Diffraction effects are therefore negligible.

The circles to the left of the sketches show respectively the appearance of the small mirrors from the secondary focus of each system.

4. The mirrors are set up at approximately the required distance apart and squarely facing each other by reflection. The exact value of the radius of curvature of the spherical mirror is not of any importance; it is only necessary that its center of curvature and the shorter conjugate focus of the secondary mirror should coincide when testing.

5. If the image of the pinhole is examined with an eyepiece before the secondary mirror is corrected, there is such a considerable difference of focus that two distinct images may be found along the line of aberration, with much dispersion of light. When the secondary is correctly figured to look perfectly flat, all the light is concentrated within the image of the pinhole, the details of which are plainly visible. The expansion of the image is the same on both sides of focus; in fact, the test is precisely similar to that of a

spherical mirror at its center of curvature. It therefore follows that the surface of the secondary mirror *must* be accurate to within a very small fraction of a wavelength.

It is obviously better to refer secondary mirrors to a spherical mirror, whose accuracy can be tested at any time by visual inspection, rather than to a combination of mirrors derived from the same source, with diminishing accuracy. It is likewise of the utmost importance to be able to produce secondary mirrors without reference to the paraboloidal mirrors with which they have to work.

6. The uncorrected secondary mirrors for Cassegrain and Gregorian telescopes show diametrically opposite appearances under the knife-edge test. The former has a protuberant, the latter a depressed, intermediate zone, at the average focus. The hyperboloid is therefore more difficult to produce, having a depression in the convex spherical surface, reaching a maximum depth at the intermediate zone, and diminishing to nothing at the edges and center. A corrected convex, if resting inside a concave spherical surface of suitable curvature, would make contact at the edge and center only. Such a figure cannot be produced haphazard, and if the depressed zone is unsymmetrical, an astigmatic image results.

7. The Gregorian concave, like the paraboloid, is corrected by excavating the center more deeply, the excavation diminishing to nothing at the edge. It can therefore, more easily than the Cassegrain, be corrected by star tests if workshop tests are unavailable, gradually making the ellipsoid deeper until full correction is attained. This probably explains the predominance of the Gregorian before workshop tests were devised.

[EDITOR'S NOTE: When Mr. Hindle's contribution on the compound telescope became available in pamphlet form, prior to its inclusion in the present volume, a number of interesting questions concerning the Hindle test arose, and were referred to him. His replies to a number of the more typical questions have been embodied in the following notes, which may settle some queries the reader might otherwise wish to make]:

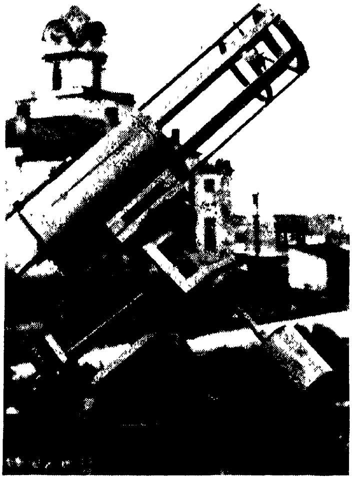
"First of all, and appropriately, it is asked, cannot a smaller test mirror be used. The answer is, yes. A set-out to scale will show how small, but at the same time, the hole must be enlarged.

Another proposal, and a futile one, is to use the principal mirror farther away from the convex, where obviously it cannot receive and return the full cone of rays, consequently the central portion of the convex only is illuminated.

Still another proposal is to use the principal mirror, in a spherical form, in a similar position, but offset so as to illuminate a circular patch on the convex, a flat being used to divert the small end of the cones at right angles to make them accessible. Apart from the extra two reflections thus involved, it should be realized how small an angle the entire convex presents under test. In the case of the Cassegrain amplifying 4 times, it is as if we were testing a 12-inch mirror directly, but *20 feet away*. In the case of

the Gregorian, we are virtually testing a 12-inch mirror *30 feet away.* Under these circumstances, we require good eyesight and the full aperture to insure a satisfactory job.

It is not generally realized that the Foucault test at the center of curvature of a concave mirror loses its delicacy as the radius of curvature shortens. For this reason, it is not wise to diminish unduly the diameter of the test mirror, and shorten its radius of curvature."—J. H. H.



A 10-inch Cassegrainian made by Paul Linde of Crossville, Tenn.

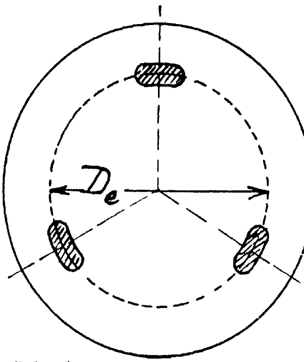
CHAPTER II.

Mechanical Flotation of Mirrors

By John H. Hindle

The enterprising and ambitious amateur telescope maker sooner or later encounters the problem of so supporting his mirror, no matter what position it assumes between horizontal and vertical on any diameter, that flexure does not occur. Small mirrors of ample thickness relative to their diameter cause no trouble, and it is perhaps difficult to fix a precise diameter at which equalizing supports become necessary. If the very finest performance is expected, anything larger than 15 inches diameter should be provided with mechanical flotation and adequate edge support.

The slightest flexure in a mirror, either induced or permanent, is easily recognisable by observing the extra-focal images of a second or third magnitude star with a very high power; and, incidentally, spherical aberration



All drawings by the author

FIGURE 1

Mirror resting on three pads set on a ring at its diameter of equilibrium, De.

can be similarly detected. But, assuming that the figure is correct and that there is no permanent astigmatism, a properly supported mirror will show a star disk expanding precisely *circular* on each side of focus. The ***slightest*** ellipticity should be regarded with suspicion, particularly if it is one way outside focus and at right angles thereto inside focus. We cannot then possibly expect the finest definition, no matter how good the seeing.

The professionals float their large mirrors mechanically, by resting them primarily on a three-point rigid support, with additional pivoted and

weighted supports to take care of individual areas of the disk. These additional weights, easily disposed in a large instrument, become a nuisance in a small one and seriously handicap a probably already overloaded structure. Some more attractive method must therefore be devised.

Shorn of technicalities, the problem resolves itself thus: The mirror must rest on a number of self-adjusting supports, geometrically symmetrical with each other in relation to the circular bearing face of the disk, and each taking an equal share of the weight. Suppose we investigate a three-point support for, say a 10-inch mirror; where would the three supports have to be located? Obviously, in a circle of such radius that the mirror is divided into two *imaginary* portions, an inner circular disk, and an outer annular ring, of equal weight and area. Thus a disk 10 inches in diameter has an area of 78.54 square inches. Half of this is 39.27 square inches, equivalent

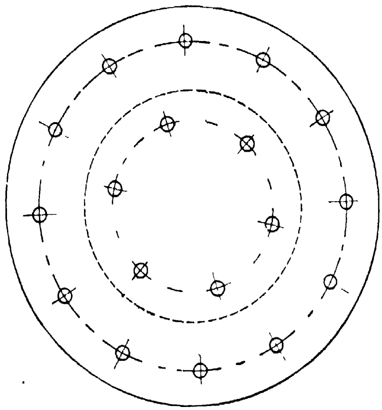


FIGURE 2

approximately to a 7-inch circle. The three supports therefore should be arranged 120° apart at $3\frac{1}{2}$ inches radius, which we shall name the *"radius of equilibrium."* Such supports will be found quite satisfactory for small mirrors, and they may take the form of a raised annular ring of 7 inches mean diameter, not more than one inch broad, at the bottom of the cell, and allow the mirror to select its own three points of support, which it will do in practice. It is preferable, however, to glue three strips of cork or felt to the surface of the seating, as shown in Figure 1, to define more accurately the areas of support.

If we now endeavor to expand our support system by pivoting a three-point support on each of our original three we find ourselves in difficulties. We now have nine points of support but, considered circumferentially, they

are not symmetrical; that is, each point cannot be arranged to support an equal area. If, however, we increase the number of points to *eighteen*, we arrive at a particularly fortuitous arrangement which is geometrically sound. Again the disk may consist of two imaginary portions, the central circle, and the outer annulus. We determine the radius of equilibrium of each, and space symmetrically *twelve* supports under the annulus, and *six* under the inner circle. (Figure 2.)

As we have *twice* the number of supports under the annulus, in comparison with the central portion, it must obviously be *twice* the weight of the latter. Considered by area, a 20-inch disk would be mentally divided up as follows:—

Area of 20-inch mirror........................314.16 sq. inches.
Area of central portion ....104.72 sq. inches.
Area of annulus ....209.44 sq. inches.

and there is no difficulty in finding the radius of equilibrium of each portion.

Arranged as in Figure 2, it will be found that a group of *three* supports, two from the outer circle, and one from the inner, make an *almost* perfect

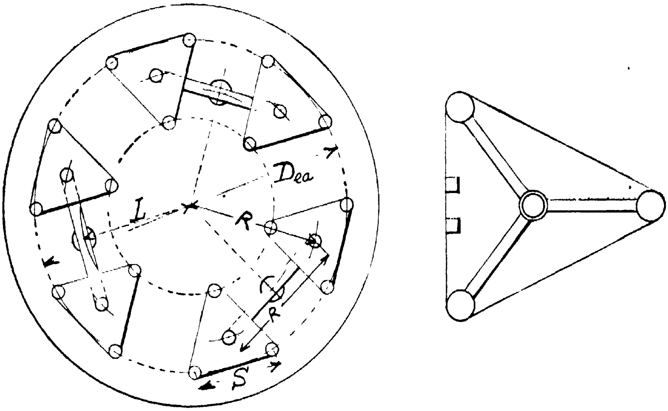


FIGURE 3

Left: How the groups are balanced on three bars. Right: Under side of a triangular support.

equilateral triangle. Two triangular plates, preferably of aluminum, combining these three points, may be spherically seated at each end of a stiff bar of rectangular section, which is again pivoted at its center to form one of our primary three-point support positions (Figure 3, left).

In practice, we ignore the radius of equilibrium of the "inner circle" but

obtain that of the annular ring, space our twelve supports equally, and make the chord joining two adjacent supports the sides of our equilateral triangle. The following formulae enable the dimensions of the support system to be calculated for any size of disk.

3-point support.

D = Diameter of disk

De = Diameter of equilibrium $= \sqrt{\frac{D^2}{2}}$

18-point support.

Dea = Diameter of equilibrium of annulus $= \sqrt{\frac{2D^2}{3}}$

$S = \left\{\begin{array}{l}\text{Distance apart outer circle of supports} \\ \text{Side of triangular support.............}\end{array}\right\} = Dea \sin 15°$

T = Radius of circle to envelop triangle $= S/2\cos 30°$

$R = \left\{\begin{array}{l}\text{Radius to center of 3-point triangular support} \\ \text{Length of pivoted bar between seatings... ..}\end{array}\right\} = T + S$

L = Radius of primary 3-point support $= R \cos 30°$

Detail drawings of the pivoted bar with its spherically seated aluminum triangular plates at each end are shown in Figure 4. The spherical hole in

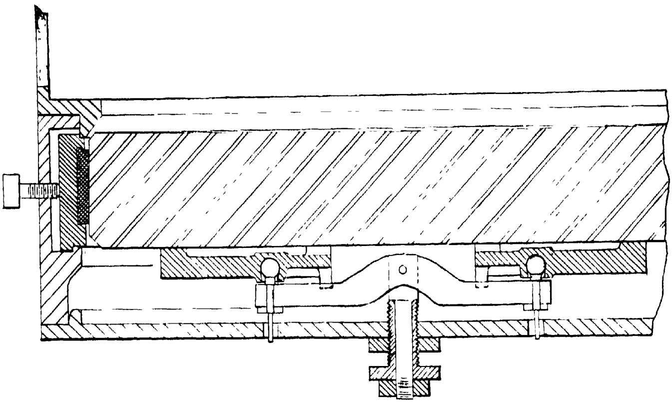


FIGURE 4

the plate is closed over the ball slightly, so that the former cannot come adrift, and there are two small lugs under each plate, which loosely straddle the pivoted bar, to prevent the plate from rotating. (Figure 3, right.) In practice the flotation is perfect, the number of support points ample, and it should not require much ingenuity to adapt this system to any size of mirror contemplated.

The edge support requires careful consideration. It must take the weight of the inclined mirror without allowing the latter to slide appreciably across the triangular supports, and yet not compress the mirror, otherwise flexure will result. It is inadvisable to have large metallic areas in contact with the edge, as that intensifies temperature effects. The best solution seems to be to envelop the mirror with a sectional ring lined with leather, or other resilient non-conducting material. In practice, the metal ring can be recessed with a slight dovetail, and the leather hammered in all round. It is then put in the lathe, and the leather bored out to the precise diameter of the mirror. The ring is then cut up into three equal portions. The cell is so designed (Figure 4) that each section can be fed forward by two set-screws, but comes against a ledge top and bottom as it finally closes on the mirror; without, of course, nipping it. No lateral movement of the mirror is now possible, and the resilient edge support is perfectly formed and in contact all round.

Should a sudden fall of temperature occur, causing the cell *as a whole* to contract before the mirror, the situation can be relieved by slightly releasing the screws of the *upper* sector or sectors (for the time being) of the edge support ring, and the axis of the paraboloid is thereby practically undisturbed.

Obviously the edge support does not necessarily need to support the full width of the edge. If it is half as wide as the edge this will be sufficient, and it is a decided advantage to bring the support slightly nearer the front edge of the mirror, so that the pressure on the back supports is never entirely relieved, even with the tube horizontal. This avoids any tendency for the back supports to become displaced.

A note added in 1935, two years after the foregoing comments were first published: The fundamental idea of a "radius of equilibrium," first published in a previous edition of A.T.M., is perfectly sound, and leads to a lighter and less cumbrous system of flotation. The contingent remarks (page 230) respecting difficulties in the way of a 9-point flotation having been criticised, it is perhaps worth while examining the conditions under which such a system can be adopted. Compared with an 18-point flotation, the "radius of equilibrium" of the annulus would be the same, $\sqrt{\frac{2D^2}{3}}$, and that of the central disk, $\sqrt{\frac{D^2}{2}}$. In each case there are half the number of flotation parts, *viz:* six in the annulus, and three in the central disk. In Figure 5 these points are connected to make three triangles, the proportions being stated in terms of the disk diameter, *D*. The long outer side of the triangle is obviously equal to the "radius of equilibrium" of the annulus. Such a triangle can be pivoted at its center of gravity, one third the way up from the base, and take an equal load on the three extremities. It must, however, be first individually balanced, and then restrained from rotation to practically its precise position, if it is to function correctly. On the other hand, rotary displacement of the equilateral triangles of the 18-point support has no serious effect; each triangle

then becomes a 3-point equilateral support to a one-sixth sector of the disk. That is the difference between the two systems.

In either case, the areas of support should be small, so as to coincide as nearly as possible with the geometrical points. Steel balls may be embedded in the aluminium casting, and a small flat ground simultaneously on

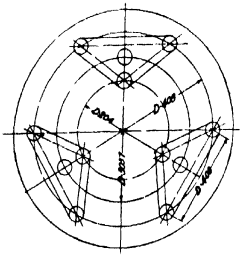


FIGURE 5
Data for a 9-point flotation system.

each by rubbing on an abrasive sheet, laid on a flat surface. This forms the least frictional contact between the support and the back of the mirror. Cork, felt, or other resilient materials are to be deprecated. Test the system by tilting the mirror slightly on different diameters and noting the angle at which sliding commences. If the tangent of this angle is not greater than the co-efficient of friction between glass and steel, we may conclude that the flotation is satisfactory.

Machine-Polishing Mirrors

By JOHN H. HINDLE

For many years, it has been continually argued that the only way to deal with small and medium-sized mirrors was to work them by hand. No machine could produce an equivalent, or even comparable, result. The wiseacre correspondents of the *English Mechanics* would promptly, so to speak, rap the knuckles of any daring individual who proposed the use of entirely mechanical methods.

Much pioneer work, in this respect, was done by Dr. Draper, who experimented with no less than seven different machines. He specifically mentions one most important point. Describing his most successful machine, he says, "The mirror was always uppermost while polishing, and being uncounterpoised, escaped to as great an extent as possible from the effects of irregular pressure. To any one who has studied the deformation of a reflecting surface, and knows how troublesome it is to support a mirror properly, the advantage is apparent."

That Draper's mirrors did not escape these or other malign influences is

proved by his lucid description of "oblique mirrors"; astigmatic effects induced, as he thought, by irregularities in the substance of the glass, due to the process of rolling the plate. Possibly the method of attaching a driving plate, or the turning of the mirror on its back without adequate support, for local corrections, or still more likely, the irregular rotation of the mirror itself, was responsible for these difficulties. The mirrors were certainly thin for their diameter, but that is no deterrent if the mirror is ground, polished, and figured face downward, without restraint, in the manner to be described.

Types of machines: These fall under two headings, one in which a straight or ovoid stroke is used, and the other producing a circular or hypocycloidal stroke. The former more nearly conforms to established methods of hand polishing, and consequently produces the most satisfactory results. Further, if we can dispense with the "handle" usually pitched on the back of the mirror, avoid the proximity of warm hands, substitute the constant attraction of gravitation for intermittent pressure applied from the shoulders, with a precise regulation and variation of the stroke and side-throw required, we shall be making a distinct advance on manual labor.

We therefore mount the polisher securely on a slowly rotating table, with the mirror face downward on top of the polisher (Figure 1). In a direct

FIGURE 1

On this machine the mirror disk floats entirely free and on top. *See page 245.*

line with the rotating table, and at equal distances on each side of it, are two other vertical spindles, with a crank and adjustable crank-pin at the upper end of each. A light metal frame, Figure 2, consisting of two pieces of angle, adjustably connected at each end by a screwed rod, rests on the back of the mirror, and has four cylindrical rubber buffers, about 1½ inches diameter and 1 inch deep, with a ⅜-inch hole in the center, bolted to the angles, and projecting downward over the periphery of the glass disk. Con-

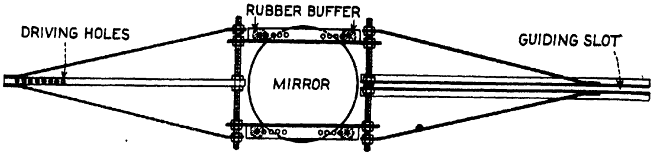


FIGURE 2
The crocodile or articulated alligator which actuates the mirror.

necting rods are attached to the screwed rods on the angle-iron frame. These rods are hinged in a vertical direction only; they must be comparatively rigid laterally (hence the side-ties), otherwise they will fail to communicate the proper motion to the mirror.

The left-hand connecting rod is drilled with a number of vertical holes for the crank pin, the geometrically correct center hole being plainly marked. The other connecting rod consists of two angles, spaced apart to form a slot, and it simply slides to and fro on the crank pin. It simplifies matters if the tail-end of the connecting rod is suspended by a cord from the ceiling, as shown in Figure 1.

Relative speeds for the three vertical spindles are as follows:—table, 1½ r.p.m.; driving spindle, 28 r.p.m.; side-throw spindle, 5 r.p.m.

Means for varying the speed are desirable. The driving spindle may run at double this speed for small mirrors.

A study of the motions of this machine shows that the mirror describes an ovoid, the size of which depends upon the radius or throw of the driving crank. This ovoid rocks from side to side under the lateral drive of the side-throw crank. Apart from the side-throw, the mean center of the ovoid need not be over the center of the polisher; in fact, there are reasons why this precise position should be avoided by choosing a suitable hole in the connecting rod.

The most important feature of the arrangement described is the *automatic rotation of the mirror*. The rubber buffers do not grip the mirror; a clearance of at least ¼ inch should be allowed. If the table and driving spindle are running in the same direction, then the mirror turns in the opposite direction. The rotation is perfectly regular if the polisher is a good fit and the mirror sufficiently heavy. The speed of rotation is governed by the clearance given to the rubber buffers, and it takes place intermittently, at each end, or during the reversal, of the stroke. The action is exactly similar to that of a silent ratchet, and the regular rotation thus induced enables excentric adjustments to be established between the mirror and the polisher, and even between the polisher and the rotating table, with perfect safety. If additional weight is desirable, it should be applied directly to the back of the mirror and not to the metal driving frame. A flat, circular weight, resting on a rubber mat, has no harmful consequences.

Grinding may be done in the same way. Here again additional weight helps to secure rotation of a thin mirror.

Continuous polishing: One of the drawbacks encountered in all polishing operations is the loss of rouge and water at the edges. This can be largely obviated by using a metal base, preferably aluminium, slightly larger than the mirror, and by turning a deep groove into the metal, around the edge of the lap, which naturally intercepts the overflow. When polishing face downward, elutriation of the rouge may be entirely dispensed with. Dangerous particles seem to gravitate to the bottom of the slots and stay there. Mixed to the consistency of thick cream, rouge is liberally distributed over the surface and into the grooves of the polisher. On starting polishing, the liquid commences frothing. Bubbles are formed, which cling to the glass and travel between the facets, even making excursions into the surrounding groove. The important function these bubbles perform is to lift the fine rouge and distribute it over the surfaces of the facets. The action is very pronounced and persists so long as frothing continues. When the bubbles tend to subside they can be revived by the addition of a little water while the machine is running.

Three or four hours continuous running may in this way be obtained for the preliminary polishing before deterioration in the color of the rouge is evident, after which the polisher may be completely washed down.

Polish obtained by these methods is exquisite and free from blemish. Danger from scratching is entirely eliminated, and in fact, some deficiency in fine grinding may be remedied. Much heavier pressure than is usually considered adequate can be safely used, and to advantage, so far as the quality of the polish is concerned.

Figure obtained by machine polishing: The amateur is conversant with the explanation given as to why the upper disk, when grinding, becomes concave, *i.e.*, the effect of "overhang." This is also the controlling factor in machine polishing. Assuming that we place the mirror centrally on the polisher, and adjust both stroke and side-throw equal to one-fourth the diameter of the mirror, we shall obtain successively an equal overhang of all parts of the disk. Stated in another way, there is a central portion of the mirror which never leaves the polisher, and an outer portion, or annulus, each part of which periodically overhangs.

If prolonged polishing now takes place, as may be expected, two distinct curvatures are produced, with the dividing line at the point of overhang.

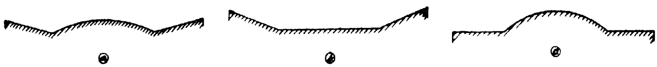


FIGURE 3

When examined at the center of curvature, the appearance at mean radius is represented at *a*, Figure 3. If we draw the knife-edge back a little we see the apparent figure, *b*. On the other hand, if we advance the knife-edge nearer the mirror, we get the tin-hat appearance, *c;* in which case, polishing away the protuberant center makes the mirror spherical.

In actual practice we carefully avoid the continued use of the sym-

metrical adjustment described. The average center of the mirror must not coincide with the geometrical center of the polisher. In fact, the polishing lap itself may also be set slightly out of center on the table, introducing another variable factor. It is purely the *regular rotation* of the mirror which permits these excentric adjustments to be introduced with beneficial results. Every 15 or 20 minutes the stroke may be altered slightly, and at intermediate intervals the driven hole in the crank may be changed. The result of all these changes, if used with good judgment, will be to bring the mirror near spherical. One most important lesson may be learned from the effects of the purely symmetrical adjustment described. There we notice that a well defined ditch or depression runs around the mirror at the point of overhang. Consequently, if we have a *protuberant* zone, we ascertain its precise distance from the edge of the mirror, and adjust the stroke and side-throw to an equivalent amount. The protuberant zone will then rapidly disappear.

This fundamental idea forms the basis of the entire policy of figuring by machine. Whichever part of the mirror we wish to attack, we make our adjustment for that particular zone to come to the edge of the polisher. If we have a turned back edge, or an over-corrected outer zone, a short stroke will quickly eliminate it. The outer edge and zones should in fact first receive attention, readings from the two outer zones being repeatedly taken. Over-correction in these zones is fatal to good performance. At first, a slightly turned up edge is sometimes advisable, as this rapidly disappears when a long stroke is used to deepen the center and obtain a regular figure.

Generally the paraboloid can be attained simply by increase of stroke. In wide angle mirrors that is barely sufficient. The center of the mirror may

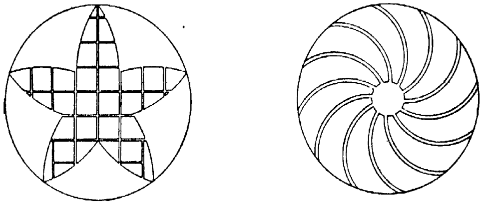


FIGURE 4
Left: Lap for operating on an umbilicus. Right: Lap for continuous polishing.

have to be brought almost coincident with the edge of the polisher to produce the required figure, and an irregularity having an umbilical formation is produced in the center of the mirror. If the various zones conform to the calculated figures this is of no moment, so far as the optical performance is concerned. Such an embellishment (on a mirror), when viewed from the center of curvature, may offend the eye, in which case the final excavation of the center may be effected by a special polisher, as shown in Figure 4, at left. We still retain the mirror on top of the polisher, but the figuring is

more rapidly performed. By reducing the outside diameter of this polisher, and limiting the stroke, we may confine its action to the central zones.

Polishing face-up: Obviously the system described permits the reversal of mirror and polisher, and it is as well to inquire under what circumstances this may legitimately be done. If we are polishing with a full-sized polisher and the mirror is properly supported on its flotation mechanism, no undesirable effects will be produced. Figuring with a smaller polisher under such circumstances is also permissible because we can, and must, rely upon the regular rotation of the mirror (also the polisher), during that operation. Particularly if the mirror has had its preliminary polish face downward, the perfect figure of revolution thus obtained will persist, if not tried too severely. Obviously we may infer that an attempt to figure entirely by hand with small polishers is out of the question. Astigmatism can most readily be recognized by the use of an eyepiece, the image of the pinhole being slightly deformed on each side of focus, while the definition, at best, is considerably impaired. There is no surer way of producing an astigmatic mirror, if the glass is sufficiently thin, than by laying it on an apparently flat surface, then polishing it without change of position.

FIGURE 5

Left: An interesting adaptation of the alligator principle to a drill press, for small mirrors. Note driver, also rope driven table. Right: Drill press and driver, with small mirror enveloped by a metal cap, being roughed out on a convex grinder.

It is certainly easier to figure with small or part-sized polishers, on the turned up face of a mirror, because the corrections may be more exactly applied, and effected more gradually. The greatest care must be used to preserve a figure of revolution, and as the risk of scratching is increased the rouge must be carefully elutriated and the polisher well waxed if we are to retain a perfect surface. If deterioration of the surface occurs, a return to the former method of polishing, face downward, will eventually restore it to its original excellence.

Hypocycloidal polishing: The use of a drill press for figuring Cassegrain mirrors has already been described (page 219), and much useful work may be done on such a machine.

The spindle being fixed, it is desirable that the rotating table can be moved slightly as the work proceeds. "Continuous polishing" is effected on a lap, shown in Figure 4, at right, which may be slightly larger than the mirror. The spiral grooves give a centripetal flow to the rouge and water, which otherwise would be dissipated. A metal cap with small central hole fits loosely on the mirror and carries it around. The speed of the spindle should be variable, and range, if possible, from 50 to 300 r.p.m. Polishing is readily effected but figuring requires some ingenuity, owing to the limitations of the stroke. However, with patience and perseverance, it is possible to completely figure small and medium-sized mirrors on this machine. It is most efficient on fine grinding. Very little material is lost over the edges, and the comparatively high speed enables the process to be quickly and most thoroughly carried out.

An interesting modification of the drill press polishing machine (page 219) is shown in Figure 5, left. The table is swivelled around from its normal position, and a small "driver" is applied to impart an ovoid movement to the mirror. We are minus the side-throw, but a similar effect is produced by occasional slight movements of the table, or by changing the hole driven by the crank. This adaption makes the drill press a really useful machine for all-around work. It must, of course, admit a table of sufficient diameter to deal with the size of mirrors contemplated.—*Witton, Blackburn, Lancashire, England, May 22, 1935.*

CHAPTER III.

Making Astronomical Flats

By JOHN M PIERCE
The Telescope Makers of Springfield.

In the "Smithsonian Contributions to Knowledge" No. 1459 (1904) now out of print,[1] Professor Ritchey tells how to make large optical flats. The present paper is an adaptation of Ritchey's treatment. The illustrations and much of the description are taken direct from that article.

Ritchey's method, which is the second of the three methods described in Part I, Ch. IX., is to cause the flat under test to intercept the rays of light between a concave mirror and a pinhole and knife-edge set up at the center of curvature of the concave mirror. A plan of this set-up is shown in Figure 1.

It will readily be seen that any inaccuracy in the flat will impress itself on the rays of light, both as they come from the lamp and as they return to the knife-edge, thus altering the characteristic shadow of the concave mirror. The effect of an inaccuracy in the flat will be doubled, since there are two reflections by it. A spherical mirror, rather than a parabolic one, is used because any change in its uniformly illuminated shadow is most easily detected. An unfinished mirror is frequently used, later being parabolized for use in a telescope.

For the flat, three pieces of polished plate glass of the diameter desired and a thickness at least one eighth of the diameter will be needed. Mark these 1, 2, 3, on their edges, with a pencil. Using the finest grit available, grind No. 1 on No. 2 for a short time, then No. 2 on No. 3, then No. 1 on No. 3, and repeat until the surfaces are evenly ground and flat, as is shown by drawing a pencil line across the ground surface of any one glass and rubbing with both of the other ground surfaces. Repeat after penciling another disk. If the line is removed in both cases, the three surfaces are relatively flat.

The pitch laps for polishing are similar to those used in mirror making. Probably two will be needed, a normal tool with uniform facets, Figure 2, and one with the facets graduated in size, for bringing a spherical surface toward the plane, Figure 3 or 4. The facets should be about an inch square.

Ritchey's directions are as follows:

"The mirrors may be set up as shown *in plan* in Figure 1, the distance *cm* plus *mf* being equal to the radius of curvature of *A*. The mirror *A* is silvered; *B* is polished but unsilvered. The light from the illuminated pinhole strikes *B*, is reflected to *A*, thence back to *B*, thence to a focus close beside the illuminated pinhole. (At the knife-edge.)

"When using the knife-edge test the optician sees the mirror *B* brilliantly illuminated, and in elliptical outline, the horizontal diameter appearing fore-

[1] See *Scientific American Supplement*, Jan. 7, 1905, in which the same papers were reprinted. This, too, is no longer available except in the files of some libraries.—*Ed.*

shortened by an amount depending upon the angle at which the mirror is viewed. With the knife-edge test the surface of B is seen in relief, as a whole; any zonal errors appear enormously exaggerated, and their character and position are readily determined, just as when a concave mirror is tested at its center of curvature; these zonal errors appear elliptical on account of their foreshortening; their effect is doubled in intensity on account of the two reflections from B. (Assuming that the illumination is as brilliant as the eye requires.)

"The test as already described is all that is necessary for the detection and location of zonal errors. But something more is necessary in order to detect general curvature, *i.e.*, convexity or concavity, in B. Let us assume

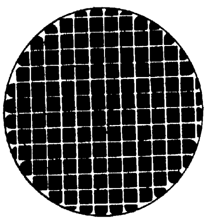


FIG. 2. NORMAL TOOL.

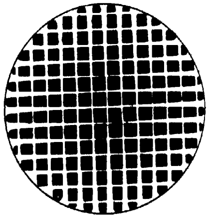


FIG. 3. CONCAVING TOOL.

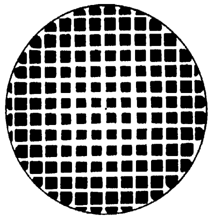


FIG. 4. CONVEXING TOOL.

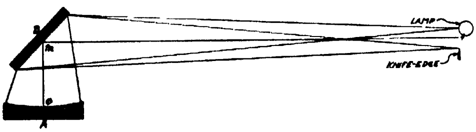


FIG. 1. PLAN DIAGRAM OF TEST FOR A PLANE MIRROR.

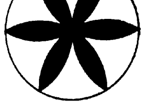


FIG. 5. ROSE TOOL.

Drawing by the author, after Ritchey

that the mirror, when fine ground and polished, is so nearly flat that no curvature can be detected with a Brown and Sharpe steel straight-edge of the finest quality; and for convenience in description let us also assume that the surface is free from zonal errors. Let the knife-edge be moved across the reflected cone from the right; the focal point is found at which the right and left sides of the mirror darken simultaneously; this focal point we will call $f1$. Now let the knife-edge be moved across the cone from above instead of from the right; a focal point will be found at which the upper and lower parts of the mirror darken simultaneously; this focal point we will call $f2$. It is only when the mirror B is a perfect plane that $f1$ and $f2$ coincide with each other and with the point f (see figure). If B is slightly convex $f1$ and $f2$ are outside of f (*i.e.*, farther from the mirror than f) and $f1$ is outside of $f2$. If B is slightly concave both $f1$ and $f2$ are inside of f and $f1$ is in-

side of $f2$. In practice the exact position of f is not found (except incidentally when the plane mirror is finished), for this would involve the very accurate measurement of the large distance *cm* plus *mf*. The determination of the positions $f1$ and $f2$ with reference to each other is all that is needed.

"That $f1$ and $f2$ do not coincide when B is convex or concave is due to the fact that the curvation of B is apparently increased or exaggerated. The effect is precisely as if the spherical mirror A were astigmatic, the parts of the surface adjacent to the horizontal diameter having a different radius of curvature from those adjacent to the vertical diameter. This effect is so marked that an extremely small deviation of B from the true plane can be detected.

"The use of an eyepiece in this test is important, because it shows how fatal to good definition is even a very slight convexity or concavity of a plane mirror when used in an oblique position. If $f1$ and $f2$ coincide as closely as can be detected with the knife-edge test (B being free from zonal irregularities also) the reflected image of the pinhole, as seen in an eyepiece at f, is as exquisitely sharp and perfect as if it were formed by the spherical mirror A alone. But if B is slightly convex or concave we get the typical astigmatic image. It is not sharp even at the best focus; if B is convex, the image becomes elongated in a vertical direction outside, and in a horizontal direction inside, of the best focus; if B is concave the directions of elongation are the reverse of these.

"The polishing is begun with the normal tool shown in Figure 2, in which the grooves are of uniform width throughout. After an hour's polishing the mirror is tested; if it is found to be convex, polishing is continued with the concaving tool shown in Figure 3, in which all the grooves are gradually widened toward the edges of the tool, so that there is a progressive decrease of action toward the edges of the glass; the amount of this widening must be determined by experiment; it should be such that the convexity of the mirror is slowly and uniformly decreased.

"If the mirror, when first tested, is found to be concave, the convexing tool shown in Figure 4 is used to continue the polishing.

"The concaving and convexing tools often tend to introduce broad slight zonal errors, hence recourse must be had repeatedly to the normal tool. When all trace of general curvature has disappeared any remaining zonal errors are eliminated by use of the normal tool.

"If a finished plane mirror is available which is not smaller than the one being figured, the work is very greatly facilitated by continually cold-pressing the polishing tools on the finished mirror; every precaution must be taken, however, to prevent injury to the figure of the polished mirror by such cold-pressing."

This is the end of the quotation from Ritchey.

Stubborn zonal irregularities may be improved by the use of small polishing tools upon protuberant zones. Rose tools (Figure 5) from 1" to 3" in diameter are excellent for this purpose. They should be of pitch on a glass

or metal base. The tool is held in the hand and worked forward and backward along the raised zone while the operator makes several revolutions around the mirror. The latter is placed on the pedestal. The tool is turned slightly between strokes. An elliptical stroke is also excellent, the "pull" part of the ellipse being along the raised zone with the worker bearing on hard; then the tool is circled back across the center of the mirror without pressure, while the operator takes a step in his path around the work, making the next stroke come at a slightly different place on the protuberant zone.

In all finishing work and especially in local polishing, as described, frequent testing is imperative. In the final stages about two minutes of polishing should be the limit between tests.

A diagonal mirror for use in a Newtonian telescope may be tested with sufficient accuracy by placing it at an angle of 45° and close to its mirror, and testing in the foregoing manner. It should be as near the mirror as possible, in order that only the central part of the large mirror, which for practical purposes is spherical, will be used.

If the flat is to be ground and polished for a diagonal it should be made in a circular form first, and after completion cut to the elliptical form needed.

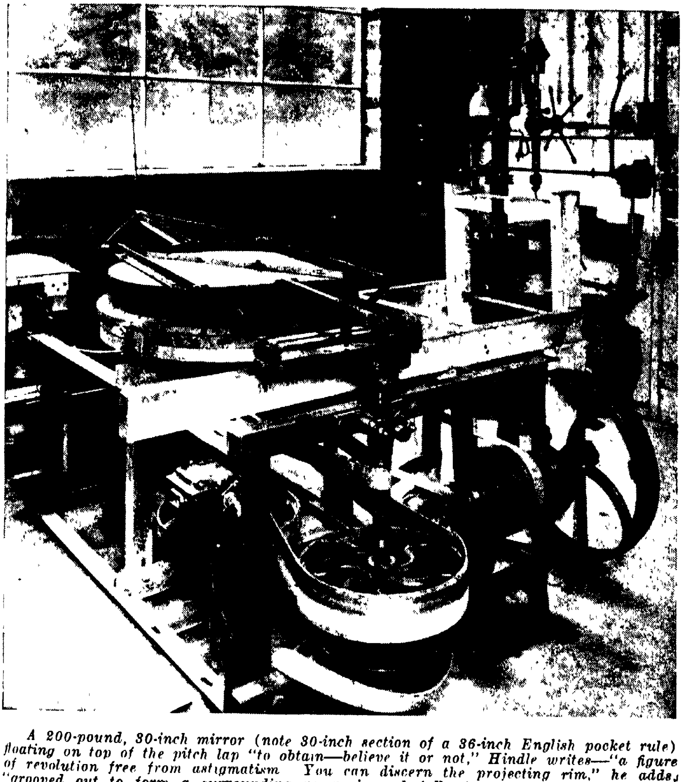
The decisive test of a diagonal is its actual performance. If a telescope functions well its diagonal is suitably flat. Frequently pieces of ordinary polished plate glass are flat enough for this purpose. To select such a piece, cut from plate glass a number of pieces of the proper size. After thoroughly cleaning them test them under a sodium light by means of their interference fringes. To prepare such a light rub common salt into the wick of an alcohol lamp, making as much salt as possible adhere to the wick. Light the lamp and place it back of a sheet of ground glass or tracing paper, in order to diffuse the light. (Part I, Figure 43.) Another good source of monochromatic light is the 2-watt 110-volt No. S-14 neon lamp made by the General Electric Vapor Lamp Co. This screws into a standard-sized socket.

Lay one of the pieces of glass on top of another and place it so that you can observe in it the reflection of the illuminated ground glass or tracing paper. (Room dark.) You will see, apparently on the glass being tested, a series of alternate black and yellow lines stretching across it. By pressing the edges of the glass you can make these lines vary in number and width. Press until they are about an eighth of an inch apart, then lay on a straightedge to see how straight they are. If straight, it shows that the adjacent surfaces are parallel to one another.

Test all your glass pieces with others until you find three that give good straight lines when tested together in all combinations; *i.e.*, 1 with 2, 2 with 3, and 1 with 3. When this condition exists the three surfaces tested are flat. Mark the back of each with a glass cutter to insure identification, and you have three glasses suitable for diagonals.

After you have a surface that you know to be flat you can test any polished piece of glass by laying it on the master flat and noticing the interference bands. When they are straight the surface is flat. If the lines

appear curved, the surface being tested is either convex or concave. To determine which, press the edges of the glass until the lines appear as complete circles with the center at the approximate center of the glass. Each circle represents about 0.00001″ departure from flat, so counting the circles will show how much must be polished away in order to bring the glass under test to the surface of the master flat being used. To determine whether the surface is convex or concave lower the head while watching the circles: if they appear to move outward from the center, it is convex. If toward the center, it is concave.



A 200-pound, 30-inch mirror (note 30-inch section of a 36-inch English pocket rule) floating on top of the pitch lap "to obtain—believe it or not," Hindle writes—"a figure of revolution free from astigmatism You can discern the projecting rim," he adds, "grooved out to form a surrounding reservoir and full of rouge liquor." Later he writes, "Figuring is now being done face up, on the 18-point flotation, which preserves the figure of revolution perfectly."

CHAPTER IV.

A Solar Spectroscope

By Rev. Harold Nelson Cutler

The construction of a spectroscope depends upon the use to which it is to be put. Bearing in mind, then, that the instrument will be subject to many variations of construction, the following chapter will describe a simple, typical spectroscope which may be used for solar investigation. The basic principles of construction will be found here, and these should enable the constructor who has mastered them, to make an instrument suitable for his own specific needs.

In working with the sun, we have such an abundance of light that we are able to make use of a spectroscope having four principal parts; the slit, the collimator, the analyzer, and the view telescope or camera.

The instrument to be described will make use of a replica grating for the analyzer. It is suitable for use with a small refractor or reflector; or, in conjunction with a plane mirror, it may be used in laboratory work, as shown in the photograph. This spectroscope was used by A. R. Dunlop of

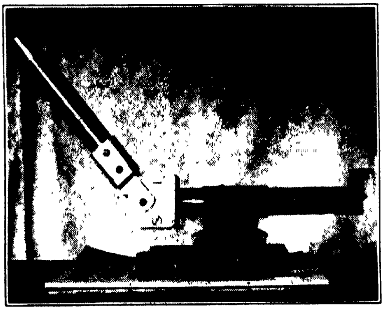


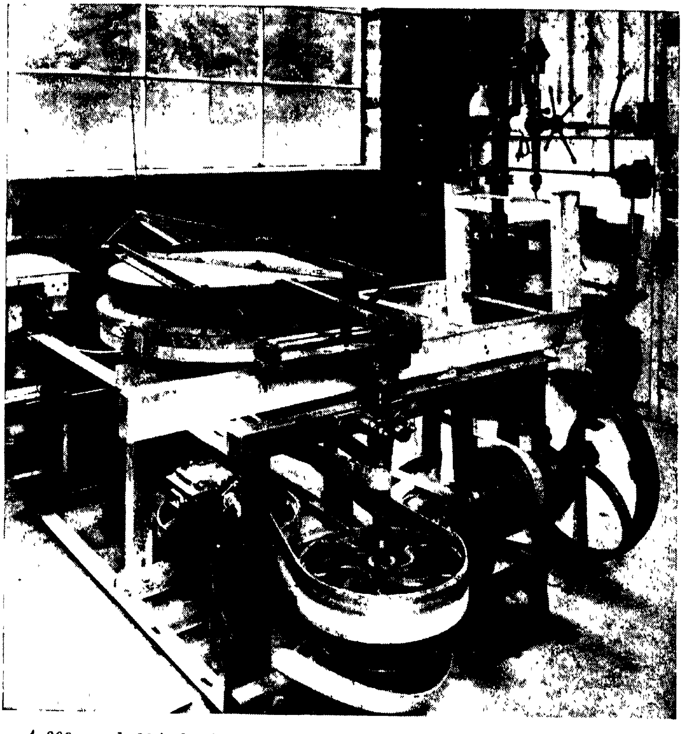
Figure 1

The solar spectroscope described in the accompanying article.

British Columbia, and the results obtained with it were described in *The Scientific American,* November, 1929. Mr. Dunlop and the writer worked out the problems connected with it over a period of years; then, using the same instrument, the writer observed the solar prominences. Therefore, in making this instrument the experimentor may feel certain that he will be making something perfectly practicable.

The photograph, Figure 1, and Figure 2 show the assembly. The materials needed consist of two achromatic objectives of excellent definition,

appear curved, the surface being tested is either convex or concave. To determine which, press the edges of the glass until the lines appear as complete circles with the center at the approximate center of the glass. Each circle represents about 0.00001″ departure from flat, so counting the circles will show how much must be polished away in order to bring the glass under test to the surface of the master flat being used. To determine whether the surface is convex or concave lower the head while watching the circles: if they appear to move outward from the center, it is convex. If toward the center, it is concave.



A 200-pound, 30-inch mirror (note 30-inch section of a 36-inch English pocket rule) floating on top of the pitch lap "to obtain—believe it or not," Hindle writes—"a figure of revolution free from astigmatism. You can discern the projecting rim," he adds, "grooved out to form a surrounding reservoir and full of rouge liquor." Later he writes, "Figuring is now being done face up, on the 18-point flotation, which preserves the figure of revolution perfectly."

The jaws themselves are made as shown in Figure 4. The beveled jaws at 24, which constitute the slit itself, should be made as accurately as possible, as the image formed is the image of this slit. Failure to sense this requirement adequately has been the chief source of disappointment in making spectroscopes. They should be milled or filed, and then ground with Carborundum and polished with rouge. A block of brass (14) with a pin or point (26) in it is affixed to the movable jaw. Against this bears the screw, which is actuated by the thumb nut (12, Figure 3). This passes through the block 13, which is fastened to the frame.

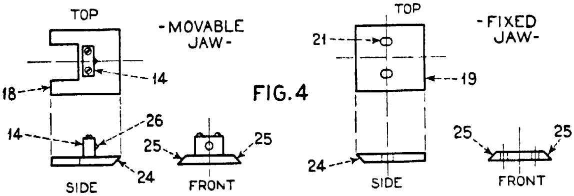
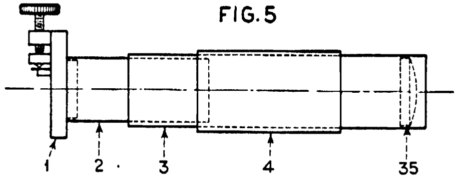


FIG. 4

The block 16, which is secured to the left-hand guide, holds the spring 17, against which the point, 26, bears. This gives tension to the whole adjustment.

The fixed jaw is provided with two enlarged holes (20) through which two screws (21) pass into the frame. As this jaw is fitted a bit loosely in the guides, it may be moved laterally, to bring it into perfect parallelism with the movable jaw. Likewise it has a slight longitudinal adjustment, for bringing the slit to the optical center of the instrument. After the two adjustments just mentioned have been made, the screws may be set up tight. A collar (22), which will serve to secure the slit to the collimator tube, is affixed to the back of the frame. It has a ½" hole bored in the center, which will coincide with that in the frame.

FIG. 5



If the slit is carefully constructed and if the movable jaw is fitted nicely to the guides, the jaws will slowly open or close as the thumbscrew is turned.

The collimator consists of a piece of brass tube (3, Figure 5) suitable in diameter to admit the collimator lens (35) and about 2" shorter than the focal length of the lens. Over this is slipped a short tube (4) to which the device used in mounting may be attached. A tube (2) is slipped inside for

focusing, and to this the slit is secured as shown. The lens is secured within the tube by two rings cut from the stock from which the focusing tube is made. The end which bears the objective fits into the short tube 27 shown in Figure 6, thus securing the collimator to the grating box.

The grating box is made of brass, as shown in Figure 6, having such dimensions that a Wallace replica grating[2] can be loosely held in the space

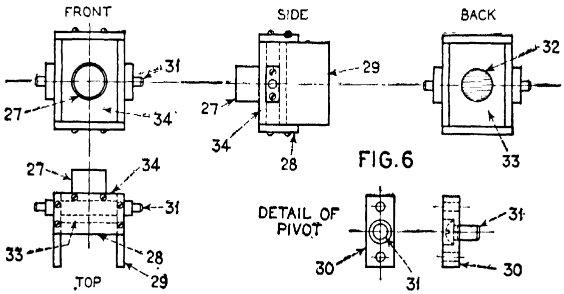


FIG. 6

between the partition 33 and the front piece 34, into which the tube 27, has been set. The detail shows the pivot on which the supports for the telescope (9, Figure 2) will be hinged. This may be omitted and the supports screwed against the box, as shown in the photograph, if sufficiently thick brass has been used. In any event the arms (7, Figure 2) should be capable of move-

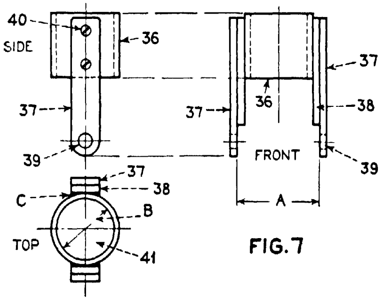


FIG. 7

ment at the point represented by 31, Figure 6, so that, by swinging the view telescope about this point, the spectra may be passed in review, and thus any line of dispersion may be selected.

The support for the telescope is shown in Figure 7. Should the pivot block shown in 30, Figure 6, be omitted, the reenforcing strip 38, Figure 7,

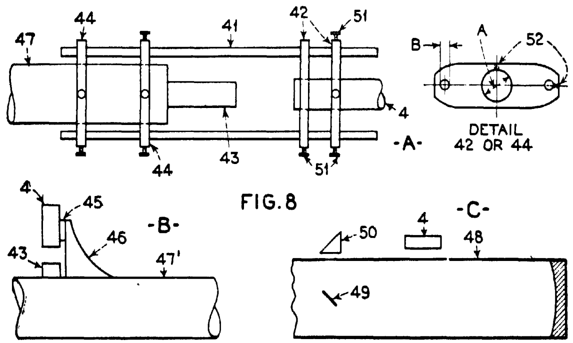
[2] Central Scientific Company—approximate cost, five or six dollars.

will be also omitted. In the present model these serve to stiffen the arms 37, 37, and to bear against the grating box, in order to lessen vibration. The short tube 36 serves to carry the view telescope. In the same diagram —Figure 7—39 represents the holes to receive the pivot. *A* gives the distance between the pivot blocks and 41 is the hole in the support for the telescope.

The view telescope is simply a small refracting telescope (hence the second objective specified) mounted as shown. A certain degree of care should be used in aligning it with the optical axis of the instrument. The interior of the whole should be blackened in order to reduce reflection.

Extraneous light may be excluded by making a little hood of dark cloth to cover the open portions of the grating box and the objective end of the telescope. In a later model the writer made the grating box semi-circular at the telescope end and much larger in dimensions, and fitted it with a slide to which the telescope was affixed, thus making the whole light-tight. But, unless such a box is made with the greatest of skill, it will stick and cause endless trouble.

Mounting such an instrument as the one just described requires some ingenuity. The photograph shows it mounted on the focusing bed of an old



camera, by means of a block of wood secured to the tube (4). Mounted in this manner it is a useful laboratory instrument. For mounting on a refractor it may be swung between two rods of sufficient diameter, as shown in Figure 8 at *A*. It may be mounted on a reflector, as shown in the same figure, at *B*. The method shown in Figure 8 at *C* has been tried but the results did not come up to expectations. The most convenient mounting will be a fixed telescope with the spectroscope mounted in a fixed position, as shown in the photograph, with the beam of light directed into it by means of a coelostat. If mounted polar fashion, with a single flat driven by clockwork, excellent results may be obtained. In Figure 8, 41 represents a pair of half-inch brass rods, 48 is the focusing tube of the telescope, with ocular

removed, 45 is a block for joining 4 and 46, and 46 is a sturdy bracket. The tube of a refracting telescope is indicated at 47 and at 48 the tube of a reflector, if that type of telescope is used. In the latter, 49 is the diagonal and 50 the prism. At 51 is a set-screw and 52 is the hole for it.

The adjustment of the spectroscope may give the worker some trouble. This is adequately dealt with in a supplementary note in Young's "The Sun." Since this book is out of print and must be obtained at second hand, the following notes may be helpful: Remove the view telescope from the instrument and focus it on a distant object. To focus the collimator remove the grating and set the telescope so as to look directly into the collimator. Move the tube carrying the slit in or out until the fine line made by the slightly opened jaws is in sharp focus. Twist the tube carrying the slit until it is perpendicular to the field of view. Replace the grating, taking care that its lines are parellel to the slit, so that the spectra may travel straight across the field of view as the telescope is moving.

The following brief notes on the use of the instrument may be helpful: If used as a laboratory instrument, the light is simply reflected to the slit by means of a mirror and the spectrum viewed. A comparison prism may be affixed to the slit, as shown in manuals.[3] When using a grating the amateur will note that, as he swings the telescope, the spectra of greater dispersion of the higher orders will come into view and may overlap each other to some extent. To view the solar prominences the limb of the sun must be sharply focused tangent to the slit and the telescope moved so that the *C* line is in the center of the field. Then the slit is opened. The prominences may then be seen if there are any at that point. It may be necessary to search the limb of the sun. It may be advisable to interpose between the eye and the eyepiece a bit of red filter, in order to exclude the other colors arising from the overlapping of the spectra of the other orders. The amateur will select an order best suited to his needs—very likely the second. A more adequate description will be found in Abbot's "The Sun."

An excellent spectrograph designed for use with a flat is described by Jack Garrison in *Popular Astronomy*, March, 1926. [Reprinted below.—*Ed.*]

A Solar Spectrograph [4]

By Jack Garrison

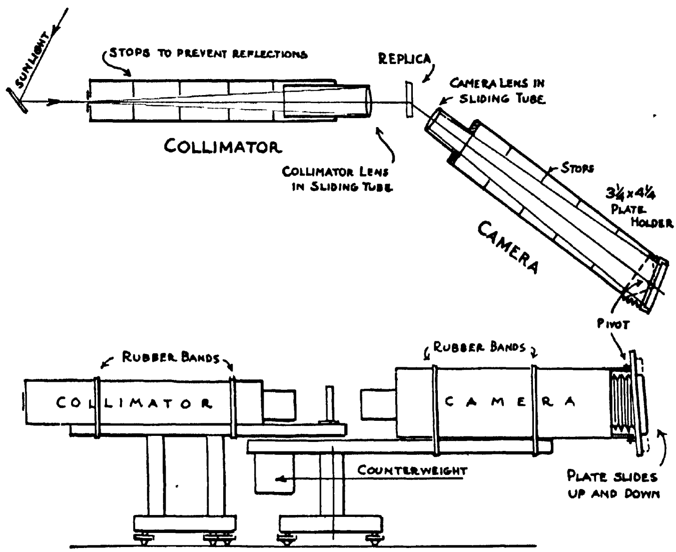
Many amateurs in astronomy never have thought to turn their attention toward the physical part of this science, but some very interesting and instructive work can be done in this direction with some home-made apparatus, which may be constructed at a very small cost, with the help of some tools and other material. So if the following instructions are carried out an instrument with which much valuable information may be gained can be built.

[3] For example, in Russell, Dugan and Stewart's "Astronomy," Vol. II, chapter on "The Analysis of Light," comparison spectra. The comparison prism is merely attached parallel to the slit.

[4] Reprinted by permission, from *Popular Astronomy*, March, 1926.

Bear in mind all the while that the main thing in constructing such an instrument is rigidity of the different parts.

Procure first two lenses from one and one-half to two inches in diameter with a focus of about 30 inches, and a good replica of a grating (a Thorps preferred) the ruling of which is about 14,000 lines per inch. Then the attention can be directed toward the building of the stand and the tubes. The collimator tube (referring to the upper part of the figure) should be made of wood and it should be about 25 inches long and 3 inches square. It should be provided with several stops or diaphragms and another tube 10



Drawings by Russell W. Porter, after the author

inches long and just large enough to slide snugly into the longer tube. This is for focusing. In the smaller tube mount one of the lenses, while in the end of the larger mount a slit. This last article may be made or purchased. This comprises the collimator and the collimator is in adjustment when the slit is at the focus of the lens.

Next the camera can be made, which, as can be seen from the figure, is another wooden box of larger dimensions, with a lens at one end and a dark slide at the other, and also notice that it is provided with stops. This box can be made of light wood about 25 inches long and 4 by 5 inches laterally. It will be noted from the figures that the dark slide is supported in such a

manner that it may be tilted sideways and be caused to slide vertically up and down. The first motion is to place the plate in such a position that all of the spectrum can be in focus at once, for it must be remembered that some colors of the spectrum are refracted more than others, and as the camera lens is not achromatic it is necessary to place the portion of the plate receiving the violet rays nearer the lens than the portion receiving the red. The second motion allows more than one spectrum, which is rather narrow, to be photographed on one plate. These two motions can be planned from the drawing, but be sure that all of the apparatus is light tight and that both tubes are blackened inside or the plates will be fogged. At the front of the box there must be the other lens mounted in a tube which must be allowed to slide in and out for focusing as shown in the plan.

Now, referring to the lower part of the figure, it will be seen that the collimator is mounted on a base which is immovable, while the base belonging to the camera has the arm pivoted upon which the latter is mounted, and that the pivot is directly below the replica grating. This is necessary so that the camera may always be pointing in the direction of the grating. After constructing these bases, the collimator and the camera can be secured to them by means of straps or, after a method of the author, by means of rubber bands cut from an old inner tube.

Now it is only necessary to place the grating in its holder and, having directed a beam of light by means of mirrors on the slit as shown in Figure 1, to move the camera into about the position shown, to cause the spectrum to appear on a ground glass screen placed in the dark slide holder. If the collimator be in focus the reversed lines of the solar spectrum can be seen.

When the instrument is well in focus some trial exposures may be tried. These must be made at the blue end of the spectrum, because the ordinary dry plate is only sensitive to the shorter vibrations. Do not be discouraged if they are not perfect, because it will require some experience to adjust the proper plate tilt and to focus the collimator and the camera.

In constructing my own instrument on this plan I was greatly assisted by Dr. George E. Hale, the director of the Mount Wilson Observatory, who personally advised me to follow this line of construction.—802 Hamilton Ave., Indianapolis, Ind.

CHAPTER V.

Celestial Photography

By Harold A. Lower

The amateur astronomer who has made a telescope of six inches or over, and mounted it equatorially, can easily use it for photographing celestial objects. If the telescope has a clock drive, or a smooth-working slow motion, interesting pictures of the stars can be made by clamping a camera to the mounting and keeping the telescope centered on a star for half an hour or more. Thirty minutes exposure with an $f/6.3$ lens will show all the stars in that section of the sky that are visible to the naked eye. Try this when there is a meteor shower, and you may catch some meteor trails.

Objects such as the moon and planets require considerable magnification, so the telescope itself must be used as the camera. Reflectors are well adapted for this purpose, as they are perfectly achromatic and do not require the use of filters.

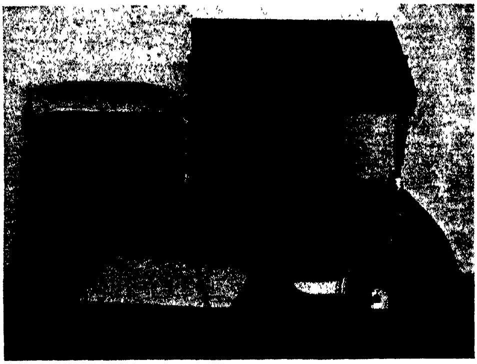


Figure 1

A simple camera attachment constructed from two tin cans which telescope smoothly. The turnbuckles provide the focusing adjustment. The eyepiece shown is used to examine the image, in order to determine when the focus is sharpest.

The image of the moon at the focus of a six-inch mirror will be about half an inch in diameter, but it is so bright that it may be magnified by an eyepiece to about an inch, and still be bright enough to photograph with an exposure of less than a second. Use an eyepiece of about one-inch focus, and project the image of the moon on a sheet of ground glass. Determine the distance from the eyepiece which is required to produce an image one

inch in diameter. Then make a box to mount over the eyepiece, which will hold a plate-holder or ground glass focusing screen at the proper distance. There should be a door in the side of the box, so that one can adjust the eyepiece until the image of the moon is sharply focused. A small reading glass is quite a help in determining when the image is the sharpest. When the focus is the best obtainable, replace the ground glass with a plate-holder. Have an assistant hold a sheet of black cardboard in front of, but not touching, the telescope. Then remove the slide of the plate-holder, look through the finder and make sure that the telescope is centered on the moon. The

FIGURE 2

A device for photographing planets through an eyepiece. The brass bushing makes the connection between the eyepiece and the tube. By shifting the plate-holder, several exposures can be made on one film.

exposure is made by moving the cardboard edgewise from in front of the telescope, and replacing it as *quickly as possible*. Be careful not to jar the telescope. If the exposure is short enough, the motion of the moon will not be rapid enough to cause a blur, even if the telescope is not equipped with a clock drive.

Do not attempt to use an ordinary camera for photographing the moon. Camera lenses do not work nearly as well as a good positive eyepiece, while the camera box just described is easily made. The size of the box is not important. If you already have a plate-holder, make the camera box to fit it. If not, get a $3\frac{1}{4}$ by $4\frac{1}{4}$-inch plate-holder, and make your box to correspond.

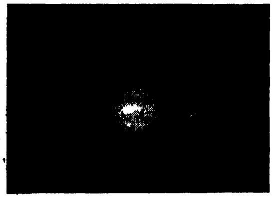
Those who have telescopes of larger size and longer focus can make pictures directly at the focus of the mirror. In order to do this, means must be provided for adjusting the plate at the focus of the mirror. The

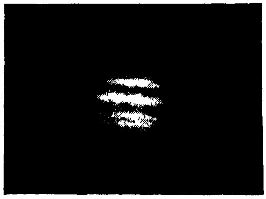
simple camera attachment shown in Figure 1 works quite well, and is easy to construct.

Photographs of the planets require much higher magnification than the moon, and the exposure must be longer. For that reason pictures of the planets should not be attempted unless the telescope is equipped with a clock drive. Instruments of eight inches aperture or more, equipped with an accurate clock, are capable of producing photographs of such objects as Jupiter and, if the seeing is good, they will show *some* surface detail. Use an eyepiece of high enough power to produce an image of the planet on the ground glass, from one eighth to one quarter inch in diameter. Exposure must be determined by experiment. From two to five seconds is long enough to record the belts of Jupiter, when using a 12-inch mirror. To photograph the satellites of Jupiter will require at least ten times as long as is needed for the planet.

The late Prof. Edward S. King recommended slow plates, well backed, for photographing the moon. It is true, slow plates give excellent contrast, but the amateur, if his instrument is not equipped with an accurate clock, *must* make his exposures short. For that reason, Eastman cut film, either super-speed or super-sensitive panchromatic, will be the most satisfactory. Both of these films are very sensitive, and must be developed in total darkness. Eastman special tube developer is convenient, and works well with these films. Time of development is four minutes, at a temperature of 65°.

For those who wish further information, "A Manual of Celestial Photography," by Professor King, is recommended. It covers the subject completely.





CHAPTER VI.

Accuracy in Parabolizing a Mirror

By FRANKLIN B. WRIGHT, M.S.

The question of how accurate the figure should be before a job of parabolizing is considered finished, may be approached in this manner: Imagine a sphere and a paraboloid with their central parts and optical axes coinciding, both with the same equivalent focal length F and diameter D. The two surfaces are spaced very nearly at a distance $e = D^4/1024F^3$ apart at the edge. This distance varies widely with the dimensions of the mirror. For an $f/8$ mirror with $D = 6$ inches and $F = 48$ inches

$$e = \frac{6 \times 6 \times 6 \times 6}{1024 \times 48 \times 48 \times 48} = 11.4 \text{ millionths of an inch.}$$

Theory and experience agree that a mirror will give practically perfect definition if it is figured so as to reduce this distance to within a quarter of the wavelength of light, that is to about 5 millionths of an inch. Taking this as a working limit, our 6 inch mirror must be figured to within 5/11.4 or 44 percent of a parabolic figure. That is, it must be figured somewhere between 56 percent and 144 percent (preferably below 100 percent to allow for thermal effects) of the theoretical amount given by the formula r^2/R or $r^2/2R$ depending on whether the pinhole is fixed, or moves along with the knife-edge in testing at the center of curvature. Table I gives the corresponding tolerance for various sizes of mirrors, including the example just cited.

TABLE I

Greatest Allowable Deviation from a Perfect Figure

Ratio F/D	D = 4″	6″	8″	10″	16″	24″	36″
4	8.2%	5.5%	4.1%	3.3%	2.1%	1.4%	0.91%
5	16	11	8.0	6.4	4.0	2.7	1.8
6	28	18	14	11	6.9	4.6	3.1
7	44	29	22	18	11	7.3	4.9
8	66	44	33	26	16	11	7.3
10	128	85	64	51	32	21	14
12	222	148	111	89	55	37	25

As this table indicates, the knife-edge position must be read with great accuracy for very short focus mirrors, while more rough and ready measurements will do with those of long focus. Those having a tolerance of over 100 percent may be finished spherical, since the sphere and paraboloid are practically coincident in these dimensions.

Nothing in these remarks should be interpreted to mean that long focus mirrors may be measured carelessly. What is meant is that precision measuring devices such as micrometer screws or vernier scales may be dispensed with except with short focus mirrors. All knife-edge measurement needs to

be done with the greatest care and freedom from personal bias. Otherwise no accurate analysis of results is possible.

Long focus mirrors with a perfectly regular appearing figure require measurement of knife-edge position in two zones only, to determine the figure. But as a general rule mirrors with any evidence of zonal irregularities, and all short focus mirrors, should be measured in many zones in order to make sure of the figure. A convenient zonal testing arrangement for the average mirror is to have the knife-edge stand slide in guides with a permanent scale fastened along one side. All readings are then taken with reference to this scale.

After obtaining a complete set of observations in all zones selected for testing, it is necessary to adjust them for the arbitrary position of the scale. This may be done by subtracting the average of the readings obtained for the zone nearest the center of the mirror; but if this zone appears irregular, by subtracting enough to make the average for a zone a little farther out check with the knife-edge formula. This is illustrated by Table II, which shows the final readings on the writer's 6½ inch reflector, compared with the theoretical readings from the formula r^2/R. Upper and lower limits of allowable deviation according to Table I are also calculated.

TABLE II

Readings in 100ths inches

Center of zone	$r = 1''$	$1\frac{5}{8}''$	$2\frac{3}{8}''$	$2\frac{7}{8}''$	$3\frac{1}{8}''$
	8.6	11.8	13.3	14.4	23.1
Original	7.6	12.2	13.3	14.4	22.1
Readings	10.1	12.2	12.2	14.7	21.8
	8.3	11.5	12.6	13.6	21.8
	10.8	12.9	12.6	13.6	22.1
Total	45.4	60.6	64.0	70.7	110.9
Average	9.1	12.1	12.8	14.1	22.2
	− 0.5	+ 2.7	+ 4.2	+ 5.3	+ 14.0
Adjusted	− 1.5	+ 3.1	+ 4.2	+ 5.3	+ 13.0
Readings	+ 1.0	+ 3.1	+ 3.1	+ 5.6	+ 12.7
(= above − 9.1)	− 0.8	+ 2.4	+ 3.5	+ 4.5	+ 12.7
	+ 1.7	+ 3.8	+ 3.5	+ 4.5	+ 13.0
Total	− 0.1	+ 15.1	+ 18.5	+ 25.2	+ 65.4
Average	0	+ 3.0	+ 3.7	+ 5.0	+ 13.1
Paraboloid	0.8	2.1	4.5	6.5	7.8
80% Correction	0.2	0.6	1.4	2.0	2.8
170% Correction	1.4	3.6	7.7	11.0	13.2

The readings were actually made to tenths of a millimeter, which accounts for the frequent repetition of the same figure in the decimal place when expressed in hundredths of inches.

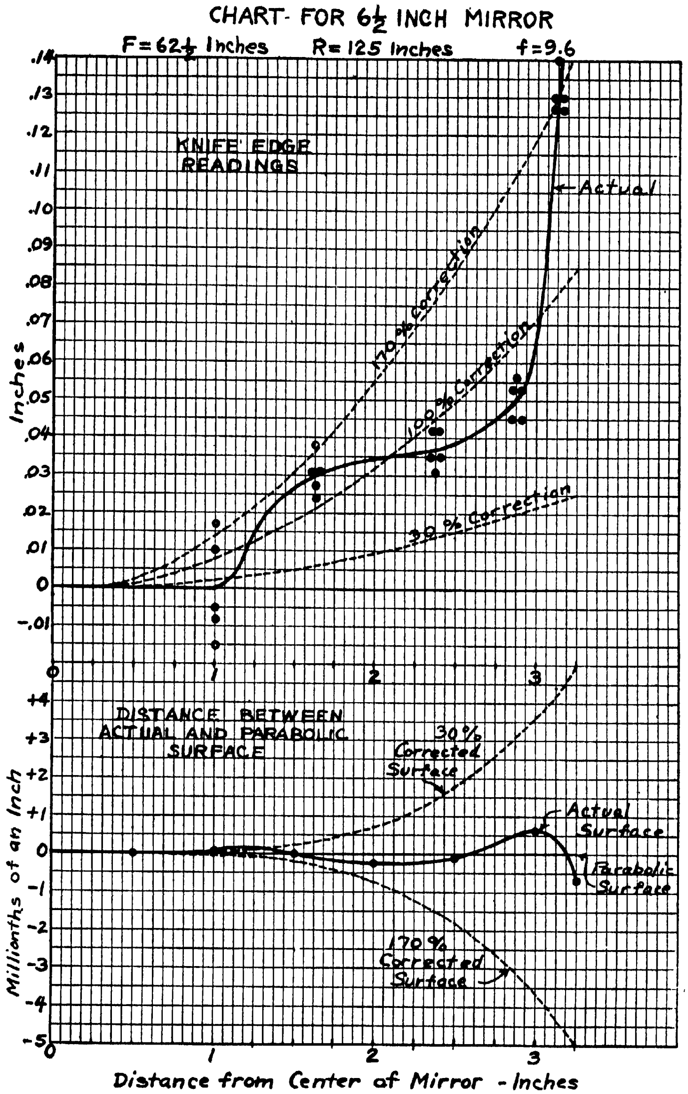


Diagram by the author

Although this table contains all the necessary information, one can get a much better idea of the figure by plotting all the adjusted readings on a chart like the full-page one shown, with curves for the theoretical readings drawn as a background. The scattering of the spots gives a good picture of how reliable the actual readings are, and a curve representing average results is easily sketched in.

In case the readings for any of the zones lie outside of the limiting curves, it is best to refigure the mirror unless adjacent zones are well within limits and the excess is not too great. Errors of curvature near the edge affect the surface more seriously than errors of similar amount near the center.

Turning again to the $6\frac{1}{2}$-inch mirror, the extreme readings just about fall within the required limits, indicating that the mirror is well figured. Although it is irregular, and the slope of the curve shows that the parts between $r = 1\frac{1}{2}$ and $2\frac{7}{8}$ inches are only about 30 percent corrected, the center and edge are over-corrected so that the curve as a whole approaches that of a 100 percent paraboloid.

Probably nine times out of ten the graph of the knife-edge readings will give all the information desired. However, it is not difficult to go a step further and reconstruct the actual surface compared with a paraboloid. Divide the graph of knife-edge readings evenly into narrow zones. Let a represent the width of a zone, r the distance from center of mirror to center of the zone, and R the radius of curvature. Let b represent the distance between the centers of curvature of paraboloid and actual surface, respectively. This is half the distance between the two curves on the knife-edge reading chart at the center of the zone (if lamp and knife-edge move together b would be the whole distance between the two curves). The actual surface is higher (in relation to the paraboloid) at the outside edge than at the inside edge of a given zone by $a \times r \times b/R^2$. These results are then summed up zone by zone, starting at the center to find how far apart the surfaces are at any point on the mirror. All this is easier to do than to explain, and the calculations are given in Table III for the $6\frac{1}{2}$-inch mirror for which R = 125 inches.

TABLE III

Width of zone, $a =$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{4}$	
Center of zone, $r =$	$\frac{1}{4}$	$\frac{3}{4}$	$1\frac{1}{4}$	$1\frac{3}{4}$	$2\frac{1}{4}$	$2\frac{3}{4}$	$3\frac{1}{8}$	
From knife-edge curves								
Paraboloid	0	.005	.013	.025	.041	.060	.078	
Actual	0	0	.015	.032	.036	.045	.131	
$b = \frac{1}{2}$ difference	0	+ .002	— .001	— .004	+ .002	+ .008	— .026	
* $a \times r \times b \div 15625 =$	0	+ .05	— .04	— .22	+ .14	+ .70	— 1.30	
* Summation	0	0	+ .05	+ .01	— .21	— .07	+ .63	— .67

* NOTE: These two lines are in millionths of an inch, other lines are in inches.

The last line is plotted on the chart, and represents to scale exactly the way the mirror would appear if tested at the principal focus with an optical flat. If any mirror is figured well enough so that this curve varies through

a range of less than 2 millionths of an inch from the lowest to the highest point, it should meet the most rigid specifications for fine optical surfaces. Even with 5 millionths of an inch the mirror will still be a good one, *provided* the curve moves gradually to this error at the extreme edge, as in the case of the 30 percent and 170 percent surfaces shown by the dotted lines, because regular surfaces like these permit most of the error to be "focused out" with the eyepiece.

All of this may seem like a lot of work, but it seems that after one has spent many months of patient work on a mirror it is worth while to spend two or three evenings analyzing the results of his labors.

It has been stated correctly by many writers that the greatest difference in optical path between rays striking various parts of an objective should not exceed ¼ of the wave-length of light. In the case of a mirror this corresponds to a surface error of ⅛ of a wave-length, since the light travels through the space in front of the mirror both before and after reflection.

If it were a fact that a telescope would be used with eyepiece or photographic plate in focus for the parabolic surface which has the same curvature at the center as the actual mirror surface, then the ¼ wave-length surface error used in computing Table I would be too liberal. However, this is not the case, because one naturally finds the best average focus for the objective as a whole, which corresponds to a paraboloid of shorter or longer focus than the one used for computing Table I, depending on whether the mirror is under-corrected or over-corrected. Assuming that it tests within the limits of Table I, and that its figure is regular (*i.e.*, spherical, ellipsoidal or hyperboloidal) the greatest separation from the nearest paraboloid will not exceed $1/16$ of a wave-length, and the greatest actual difference in light path will not exceed twice this, or ⅛ of a wave-length.

A useful variation of the method of adjusting actual knife-edge readings for the arbitrary position of the scale (see page 258, third paragraph) is to subtract an amount from each reading which will make the average of the adjusted readings equal the average of the values of r^2/R for all the zones measured. This method is for making a comparison of the actual surface with the paraboloid of closest fit. It is suggested that the reader carry out this method completely for the 170 percent corrected surface whose knife-edge readings are given in the last line of Table II, in order to verify approximately the writer's statement about the $1/16$ of a wave-length surface error.

CHAPTER VII.

Where Is the Crest of the Doughnut?

A Study in Shadows

By A. W. Everest

The answer to this question is, "Anywhere, depending upon the position of the knife-edge between the inside and outside centers of curvature." Therefore we shall revise the question and ask, "Where is the crest when the knife-edge is *exactly half-way between* the center of curvature of the inside zone and the center of curvature of the outside zone?" We shall call this the "half-way zone" and the answer is, "70 percent of the mirror's radius from the center of the mirror." (70.71 percent, to be exact, this being easily calculated by means of the familiar formula r^2/R; or $r^2/2R$, as you prefer.)

Fix this "70 percent" firmly in your mind, for the same percentage (the proof this time involves complicated mathematics) is used to locate the points of greatest apparent slope in the central depression. These points are important because they, in turn, locate the boundaries of the three paraboloidal shadows.

Let us inspect these three shadows for the half-way zone.

Referring to Figure 1:

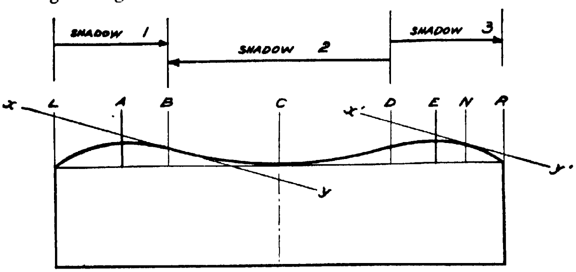


Fig 1

Drawings by the author

Crests *A* and *E* are located 70 percent of the mirror's radius from the center of the mirror.

Shadow boundaries *B* and *D* are located 70 percent of the distance *AC* or *EC* from the center of the mirror.

Shadow 1 (on the drawing) advances toward the center from the left hand edge of the mirror, over crest *A* to the boundary *B*.

Shadow 2 starts at boundary *D* and advances toward the left, across the center of the mirror to *B*, reaching that point at the same time as shadow 1.

Shadow 3 starts from D at the same time as shadow 2, advances to the right over crest E, and thence "down" off the right hand edge of the mirror.

Shadows 2 and 3 start at the time shadow 1 has reached a point between L and A having the same apparent slope as that at D.

Shadows 1 and 2 meet and disappear at point B when shadow 3 has reached a point N between E and R having the same apparent slope $x'y'$ as the slope xy at B.

Now let us inspect the apparent cross-section and the three shadows for the "outside zone" (when the knife-edge is at the outside center of curvature).

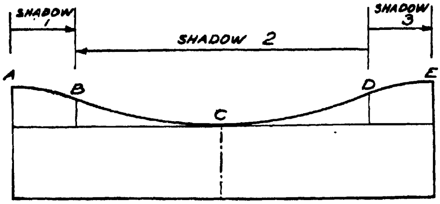


fig. 2

Referring to Figure 2:

Crests A and E are now at the edges of the mirror.

Shadow boundaries B and D are, as before, 70 per cent of AC or EC from the center of the mirror.

Each shadow travels in the same direction it traveled in the half-way zone, but the timing is different.

Shadows 2 and 3 start first, in opposite directions from D.

Shadow 3 is just disappearing off the right hand edge of the mirror when shadow 2 has reached the center. At this instant also, shadow 1 is just coming in from the left hand edge of the mirror.

Shadows 1 and 2 then continue until they meet and disappear at B.

In making practical application of the phenomena just described to the testing of mirrors we are concerned only with shadows 1 and 3. To test the half-way zone, or any other intermediate zone, we place the knife-edge in the proper position and hang a piece of wood about 3/16-inch square across the horizontal diameter of the mirror, with two pieces of pin driven in at the points where the crest should be. If the last wisps of light at the edges of shadows 1 and 3 reach their respective points at exactly the same instant. the zone tests true. In testing the outside zone, we first watch shadow 3 and note the point at which the last wisps of light are just passing off the right hand edge of the mirror. Then, if the completely darkened edge of shadow 1 is just entering the mirror at the left, this zone also tests true. It is interesting to note that at the time the readings are taken on both of the above tests, the edge of shadow 2 will have just reached the center of the mirror.

CHAPTER VIII.

The Ronchi Test for Mirrors

By ALAN R. KIRKHAM
Amateur Telescope Makers and Astronomers of Tacoma.

It seems almost undisputed that the greatest single advance in mirror making came with the announcement in 1859 of Foucault's test, making it possible for the first time really to see the figure of a mirror. Unfortunately, as is almost equally undisputed, a great deal of skill is necessary in order to decide by that test when we have very precisely what we want. Only an artist, who is "born and not made," can say with certainty whether a mirror has a *perfectly* regular curve and no turned edge.

With the more recent popularity of the Cassegrainian and Gregorian telescopes having primary mirrors of extremely short focal ratio, this difficulty has become many times greater. The edge of a short-focus paraboloid is so deep in the parabolic shadows that decision is very difficult, and the matter is further complicated by diffraction effects. A customary method of checking up on the regularity of the curve is to make a number of stops and to test five or six zones, which is often disconcerting to the eyesight, besides requiring much time and some genius. How much better it would be if one could at a glance *see* the contour of the reflector in its entirety. Very well, we have it—the Ronchi test.

The Ronchi test for mirrors is not new, and in its simplest form it has probably been in use for years. Although it has been characterized as a modification of Foucault's test, there really is very little resemblance between the two and, when performed in this way, all of the advantages peculiar to the test are lost. The Ronchi effect may, however, be produced with the Foucault test equipment, in the following manner: Move the knife-edge toward the mirror a distance beyond the center of curvature of the central zone. This will cause its shadow to fall entirely upon one side of the mirror, as in shadowgraph *B*, Part I, Figure 10. Irregularities will now be shown by a distortion at the edge of the shadow, the shadow apparently bending out toward the center into raised areas, and drawing in from low ones. A sphere is the only figure which shows the knife-edge shadow perfectly straight clear across the mirror in these circumstances. If the mirror is an ellipsoid, paraboloid or hyperboloid, the knife-edge shadow will be concave away from the center, that being an area depressed below the sphere. If the mirror is an oblate spheroid, the opposite will be true.

If, in place of the knife-edge, a very narrow obstruction is now substituted, it may not cover the entire mirror at once but, instead, will cause a dark band to appear, with both edges distorted in relation to the figure—somewhat as in *C*, Figure 1. Furthermore, if a great number of very fine obstructions are used, we shall have in effect a number of knife-edges coming both ways at one time, and the mirror will show dark bands similar in appearance (but not, of course, in actual origin) to those produced by inter-

ference, in testing a flat against its mate. A still further improvement will come with elongating the illuminating pinhole into a slit, parallel with the obstructing lines. This is the original version of the Ronchi test. Figure 2. (Described 1925, in *La Prova dei Sistema Ottica,* by Vasco Ronchi, Bologna. See also *Revue d'Optique* 1926. Ronchi is pronounced Ron'kee.—*Ed.*)

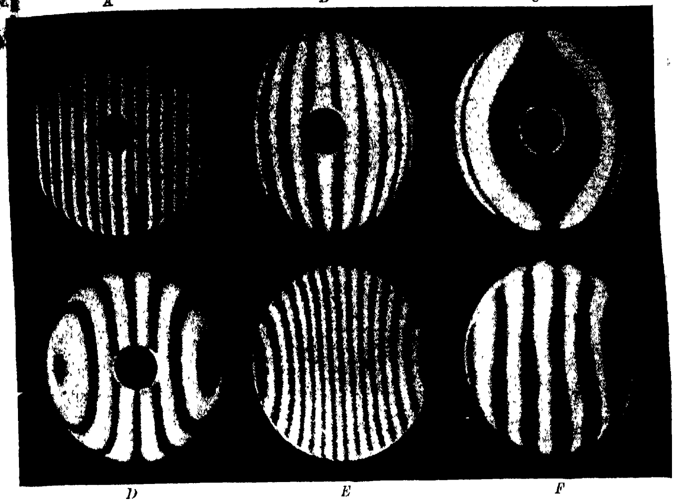
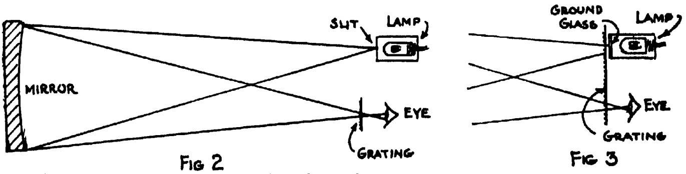


FIGURE 1

Top row Left: A sphere exhibits straight bands (this particular one also has a turned-down edge). Center. A paraboloid exhibits bands having a parabolical sweep. Right Same mirror as at center, but with grating closer to focus. Lower row. Left. Outside of focus the bands curve opposite to those inside of focus (compare with upper, right). Center Oblate spheroid inside of focus. Again note that the bands are the shape of the actual curve on the mirror—in this case, for an oblate spheroid, having a shorter radius at the ends. Right The unbeautiful result of an attempt to make a ronchigram by means of a slit and without a lens.

In practice, a grating is used having 40 to 200 lines to the inch, such as a piece of half-tone engraver's grating, or a photographic reproduction of one. Most of the accompanying photographs were made with silk bolting cloth having 135 threads to the inch, and this is very satisfactory. Pieces may be obtained, usually gratis, from flour mills, being fragments of larger cloths rendered useless to the miller because of localized holes, or from dealers in miller's supplies. The threads running horizontally do not show because the slit is longer than the interval between them. The purpose of the gratings of silk cloth is to avoid diffused light which tends to blind the

eye and destroy the knife-sharp edges of the shadows. Most photographic reproductions of engraver's gratings with which I have had experience have been objectionable for another reason: they have a strong diffraction effect which may cause prismatic colors and nearly always results in showing two or three mirrors instead of one. The emulsion between the lines on the grating is never perfectly transparent and thus the mirror is always seen as



Drawings by Russell W. Porter, after the author

FIGURE 2

The original set-up as devised by Ronchi.

FIGURE 3

The Anderson-Porter modification of the original Ronchi set-up. The same grating extends over both bundles of rays.

if surrounded by a heavy fog. Those who have access to a lathe may make a very fine grating by threading the edge of a piece of brass with 60 to 100 threads to the inch, winding on it wire (about No. 36, B & S) under tension, soldering at top and bottom and removing the wire from one side, as shown in Figure 4.

The more lines to the inch in the grating, the more bands will appear

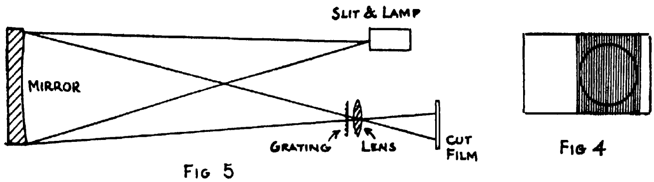


FIGURE 4

A grating made of fine wires.

FIGURE 5

The set-up for making ronchigrams.

on the mirror a given distance inside focus; that, however, being the only effect due to this cause. The farther the grating is moved from the focus, the less will be the sensitivity of the test, hence it is advisable to use a fairly large number of lines per inch in the grating, thus providing from six to twelve bands on the mirror when the grating is still near enough to the focus

to get sharp distortion. In order to avoid confusion, it is best to test with the grating always inside of the focus.

The customary and a perfectly satisfactory light source is a slit, parallel with the lines in the grating, Figure 2. It is difficult to overdo the matter of narrowness of the slit. A good way of producing a suitably narrow one is to press a razor barely through a piece of heavy lead foil or brass shim stock, making sure that the slit is not pried apart in the operation. Another arrangement of the light source, devised by Anderson and Porter (see *Astrophysical Journal,* October 1929.—*Ed.*) allows the grating to extend over the lamp. Figure 3. This, in effect, is a multiple slit. It has the advantages that the worker may move his head a bit without causing the mirror to vanish, and that the lines over the lamp must necessarily always be parallel with those before the eye. The eye sees light from only one of the grating slits at a time, and when the eye is moved, it passes from one to another without consciousness of the change. The camera does not make this distinction, and a slit is necessary if the test is to be photographed.

In the accompanying series of photographs, Figure 1, *A* is a sphere with a turned-down edge. *B* is a parabola of $f/3$ focal ratio, *C* being the same mirror with the grating nearer to the focus; note how much more clearly the figure is seen. *D* is the same mirror with the grating outside focus where the bands curve in an exactly opposite manner. Compare this with *E,* an oblate spheroid inside focus. A hyperbola looks somewhat like a parabola, the main difference being a greater curving of the bands. An ellipsoid would show less curvature. A mirror having a long focal ratio of $f/7$ or $f/8$ should show scarcely any curvature at all.

While the bands should continue regularly, clear off the edge of the mirror, one must not condemn a mirror for showing as much turned-down edge as *A* or *E,* covering less than one-fortieth of an inch of the rim, for this would be altogether invisible by Foucault's test. The remainder of the band should, however, be perfectly regular, and can be made so by perseverance and a strong right arm.

The Ronchi test may be used to measure very simply the overall correction of a mirror, in the following manner. Adjust the grating so that the two bands at the center of the disk are, say, one inch apart, and mark its position. Now move the grating back so that the bands are one inch apart at the rim. This move should amount to r^2/R, if the correction is right. Intermediate zones may be measured in the same manner, though it is quite easy to judge by sight when the bands are evenly curved, and the overall correction is therefore all it is really necessary to measure.

It is of interest to move the grating slowly and watch the bands roll across. This, in the case of a short focus paraboloid, gives an appearance like that of a barrel rolling about, while low or high irregularities will make parts of the bands seem to lag or jump ahead. With a pinhole instead of a grating a parabola will resemble a golf ball.

The Ronchi test is very useful in figuring secondary mirrors for compound telescopes by Ritchey's, Hindle's or the direct focal methods (Ch. IX). The bands should be straight. The same applies to a flat tested against a

spherical mirror, an achromatic objective lens by Ellison's auto-collimation test, or a paraboloid tested at its focus by means of a flat.

Gratings made from spider-webs and other very fine material have been proposed. This is neither desirable nor would its use be possible, since the finer the lines of the grating are made, the narrower the slit must be, and the average worker cannot carry this far, even with wider gratings. Gratings having several hundred lines to the inch have also been suggested, but they too would fail for the above reason. It is safe to say that any amateur who succeeds in making a mirror which shows no defects with a grating having 100 lines to the inch is justified in considering himself an expert mirror maker.

In photographing the Ronchi test some precautions are to be observed. While Foucault focograms are usually made with the camera lens removed, this cannot be done with ronchigrams, for the length of the slit would cause them to be gibbous, *F*, Figure 1, and their sharpness would be lost. Of course, the trouble could be avoided by using a pinhole, but this destroys the brilliant, sharp contrast between dark and light. The ordinary camera lens is satisfactory for photographing tests on mirrors of focal ratio $f/3$ to $f/4$. Above that, the ronchigrams become very small. Very best results on short-focus mirrors may be had with a lens of some eight or nine inch focus; while a mirror of $f/7$ or $f/8$ should be photographed with a lens of at least 15-inch focus. In any case, the lens is placed directly back of and almost touching the grating, Figure 5, and the film a little farther back of that than the focus of the lens. It is best to use Eastman cut film and to work in the dark. One can then see the image being photographed. Incidentally, the lens used need not be of high quality, nor even achromatic. Very splendid photographs may be taken with a ten-cent-store toy reading glass, or other low-grade lens. The time of exposure depends on so many different factors that the best way of judging is to make three test photographs of, say, one, five and fifteen minutes, exposure.

Notes on the Ronchi Band Patterns

By Russell W. Porter

The Ronchi band patterns shown in the plate[1] are the appearances of a 3¾-inch mirror of 36-inch radius with a grating of 175 lines per inch interposed between the mirror and the observer. The light from a 2-volt flashlight bulb, first diffused by ground glass, passes through one half of the grating on its way to the mirror, returning to the eye through the other half.

The mirror was not truly spherical, having a central area of 0.016-inch longer radius than that of the marginal zone. The ronchigram at *i* shows the knife-edge appearance of the mirror if the knife-edge were placed at the focus of its outer zone.

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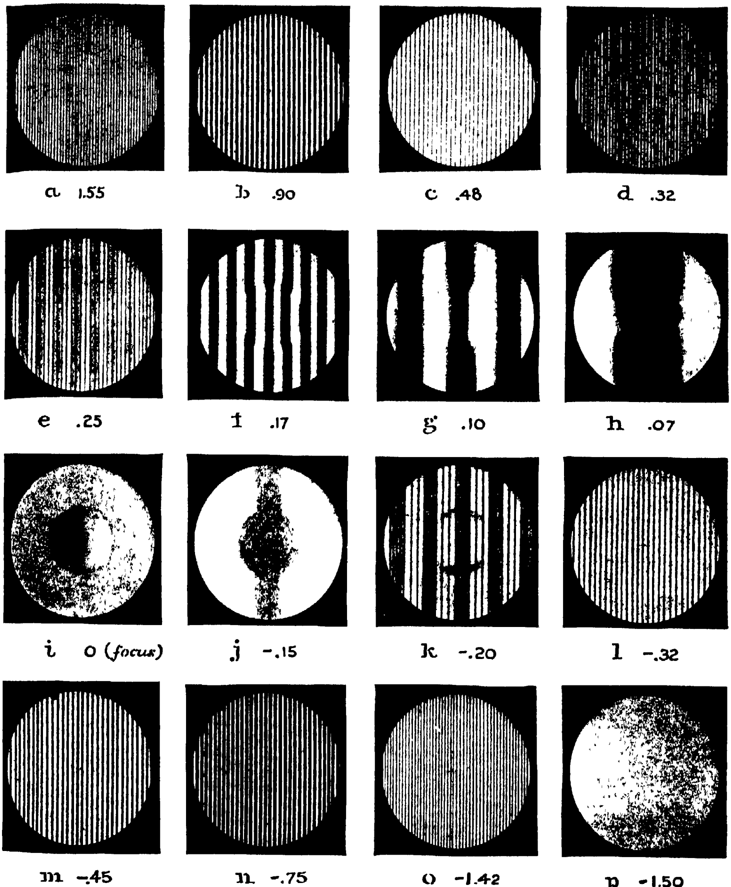
[1] Reproduced by permission, from *Astrophysical Journal*, October 1929. "Ronchi's Method of Optical Testing," by Anderson and Porter.



Drawings by Russell W. Porter

Appearance of grating patterns of a concave silvered mirror, as seen at various distances inside and outside the center of curvature. The distances are given in inches.

The Ronchi patterns seen through an engraver's screen are not perfectly sharp around the circumference. Various diffraction orders tend to blur the right and left hand edges of the disk. In drawing the patterns reproduced here I intentionally omitted the blurred areas, in order to show more clearly the character of the patterns produced by the grating when placed at stated distances from the focal plane of the mirror (near its center of curvature, not at the focus).

The drawings of these patterns start with the grating about $1\frac{1}{2}$ inches inside the focus (a), and show the progressive changes up to the time the grating is at the focus (i); and then on through seven more positions (j–p), where the lines become too fine to be seen. It will be noticed that the most sensitive, and therefore most desirable, position of the grating is just inside the center of curvature of the mirror, as at g and h. The patterns here shown are separated by intervals of confusion where the superposition of different line series do not give characteristic figures.

As the center of curvature is approached the bands spread out rapidly and reveal the features which indicate the character of the mirror surface. The positions chosen between f and i are arbitrary, as there are here no intervals of confusion.

At h, .07 inch inside focus, the first wide band just covers the apparently raised central part of the mirror. Were this the only criterion for detecting surface errors the interpretation would not be clear. But, by moving the grating slightly nearer the center, the band continues to spread out until it covers the whole mirror. If then the grating is shifted laterally so that the broadened band advances from the left, we see the shadow pattern i, which is exactly the appearance under the knife-edge when the latter is at the center of curvature of the outer zone. Hence, for this particular position of the grating, the shadows may be interpreted as in the Foucault test. The contour is determined by remembering that, if the band advances from the *left,* the resulting shadow models the surface of the mirror as though illuminated by light coming from the *right* at grazing incidence.

It was not anticipated, when developing this modification of the Ronchi test, that its application to mirror inspection would be found as useful as that for lenses. But amateurs seem to be adopting it as a supplement to the knife-edge, and with the improvement of Kirkham in the use of woven mesh screens or wire gratings, the method may come into quite general use.

CHAPTER IX.

The Direct Focal Test for Gregorian Secondaries

By Alan R. Kirkham

Much of the acclaim which rightly belongs to the compound telescope has been withheld as soon as it became evident to the amateur that he must make a second mirror at least as large as the primary paraboloid in order scientifically to figure the little secondary. In any case, before deciding to make a Gregorian telescope, it is well to recognize that the field in this type of telescope is small, and that in all circumstances the telescope will be worthless for daytime use. On the other hand, this type of telescope may be built and correctly figured, without the trouble of making a flat or a spherical mirror.

In order that the testing, adjusting, and use of a Gregorian telescope may be more intelligently considered, it is well to investigate at some length the function of the two mirrors, and we shall perhaps obtain the best perspective

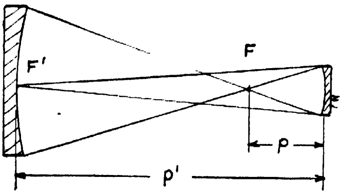


Fig 1

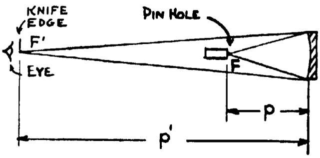


Fig 2

Drawings by Russell W. Porter, after the author

of the matter by beginning with the paraboloidal primary. The purpose of this mirror is to collect from a distant object as much light as its aperture permits. It brings this light to a focus at F, Figure 1. Here there exists a *real* image of the object, rather small if the paraboloid is of short focal ratio.

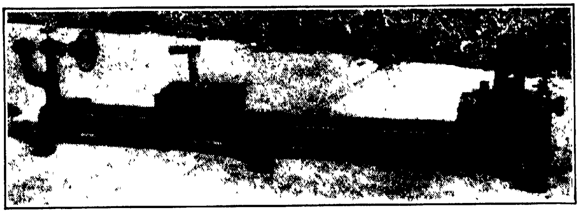
The primary mirror has now performed its function, and may hereafter be completely disregarded, and the real image regarded during the remainder of the investigation as if it were a little photograph placed at F.

It is now desired to enlarge this little image, exactly as in making a photographic enlargement from a small negative. A concave mirror of correct radius is placed a given distance p from the primary image F, and reflects this image to another focus F', at a distance p'. The amount of enlargement (amplifying ratio) is p'/p.

Now it is an interesting and a useful geometrical property of the ellipse that light originating at one of its foci (such as F or F') will be reflected back to the other. Therefore the secondary mirror must be an ellipsoid.

This immediately suggests a simple and delicate test to be used in figuring the ellipsoid, making direct use of its two foci. Simply by placing the pinhole at a distance p from the mirror, and the knife-edge at the distance p' (that is to say, at F and F'), the knife-edge should cause the mirror to darken evenly all over, just as it does in the case of a sphere at the center of curvature; or by the Ronchi test, it should show straight bands.

The arrangement is shown in Figure 2, all values being the same as in Figure 1. Since the image at F' of the pinhole at F is enlarged, the test is more delicate than a center-of-curvature test. Incidentally, it is advisable to usé a smaller pinhole, or slit if a slit is used, than is customary. In this test there is only one reflection of light, and this is much easier to find than is the case when a greater number of reflections are involved. Also there is no opportunity to make errors due to the figure of the test mirrors.



The author's set-up for making the direct focal test for Gregorian secondaries.

The light source may be a radio dial lamp operated from a small step-down transformer, or from batteries. The small size of these lamps makes it possible to place the entire lamp housing and pinhole directly in front of the mirror, provided the latter is two inches or more in diameter. Smaller sizes can be tested by using a quarter-inch right-angled prism illuminated from the side. In this case the pinhole should be on the square side of the prism, and the one which faces the mirror. The knife-edge and its adjustments are entirely orthodox.

A common tendency when designing compound telescopes, one which seriously reduces the effective field of good definition, is to make the secondary mirror too small in diameter. If this mirror is placed one fourth of the primary focal length outside of focus, its size should be considerably larger than one fourth of the diameter of the primary. Only the truly axial cone of light falls concentrically upon the secondary, all others falling somewhat to one side. The secondary should therefore be large enough to catch all of the light from all parts of the useful field. A good rule to follow, if the telescope is for visual use, is to make the secondary one fourth larger than seems necessary, and still larger if the telescope is to be used for photography—for example, to show the entire moon. The effect of making it too small is simply to reduce the aperture of the telescope to out-of-axis cones of light.

It is interesting to note that the figuring of the secondary, which can be done so perfectly and simply, is not nearly so important as that of the primary, which must be fully and perfectly corrected. An error giving rise to only .01 inch of longitudinal aberration will result in a good fraction of an inch aberration in the final combination. Errors of one tenth of an inch are not uncommon, and such would result in a final aberration of two or three inches along the axis. Of course, the equivalent focus of a Gregorian generally is very long, and the circle of confusion is not increased as much in proportion to the longitudinal aberration as is the case with the shorter focus Newtonian. Naturally, every effort should be made to arrive at the highest possible degree of perfection in figuring the mirrors, especially the primary.

Do not attempt to make a Gregorian with a long focus primary mirror. About $f/5$ is the upper limit, and $f/3$ or $f/4$ is better. Otherwise the equivalent focal length of the finished telescope will be unduly long—over $f/30$, and no eyepieces of the characteristics required for such a telescope are in existence; neither would they be desirable if they were.

The following discussion is for the advanced amateur who desires to know how things happen and it may be skipped by those whose intention is to make but one Gregorian telescope, especially if made to more or less usual specifications.

A sphere is a figure having no eccentricity. It has but one focus, that being at the center of curvature; or it might also be regarded as having two

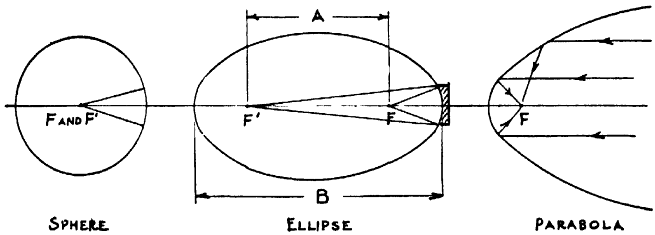


FIG 3

F' for the parabola lies at infinite distance to the right.

foci, but superposed at the center of curvature. (Figure 3.) A parabola has two foci, one where the eyepiece is placed in the telescope, the other infinitely beyond. Between these two figures, there exist an infinite number of shapes under the general classification of ellipses, having two foci which are separated more or less, this separation determining their eccentricity. In Figure 3, center, the distance A, divided by the distance B, represents the eccentricity. When the foci F and F' are separated by an infinite distance

(as in a parabola), the eccentricity is said to be 1. Thus it is seen that the eccentricity of a Gregorian secondary is

$$\frac{p'-p}{p'+p}.$$

Where it is desired to know the distance p or p' with a mirror of given solar focus f, the equation $(p-f)\ (p'-f)=f^2$ is solved for p, or p'. Thus:

$$p=\frac{f^2}{p'-f}+f\ (I).\quad p'=\frac{f^2}{p-f}+f\ (II)$$

These formulae also apply in the case of the Cassegrainian secondary, though here it is necessary to remember that p becomes a negative number. It is this fact which makes the Hindle spherical test mirror necessary. Its function is to supply a negative incident cone, a thing which a pinhole cannot do.

It is easy to calculate the effect of errors in the primary upon the secondary focus, by adding or subtracting one fourth of the longitudinal error of the primary, tested at the center of curvature, to p in the formulae (I), and solving for p'. The final aberration is the difference between this result and the result derived from solving the same equation for p' without introducing the error into p. If the error is toward undercorrection, one-fourth of its value is subtracted from p in the above equation. If it is toward overcorrection, the value is added to p. By working out a few examples one will realize how necessary it is to have the primary fully and perfectly corrected. Any very serious deviation will render the telescope completely useless.

[Editor's Note: The idea of the direct focal test for Gregorian secondaries, described above, was also hit on by Orlando Blyholder of Hillside, New Jersey. Mr. Kirkham worked it out in practice and reported the results. In commenting on the same test Mr. Kirkham modestly observes that it is a simple thing, obvious and inherent in the geometry of the ellipse. However, all discoveries are obvious—*after* they have been made.]

CHAPTER X.

A Simple, Inexpensive and Effective Clock Drive for Small Telescopes *

By F. J. Sellers, F.R.A.S., M.I.Mech.E.

I fitted the arrangement, here described, to my smaller telescope, of 3-inch aperture, which I use chiefly for examining the sun, about twelve months ago and have used it continuously since with the utmost satisfaction. Necessarily, such a drive is not perfect, but I find that it approaches very closely in efficiency to that of the usual clock drive fitted to these small telescopes. Mine will keep an object within a fairly high-power field for an hour and, while not quite good enough to keep a prominence on the slit (though it will often do this, even, for a time), will keep the limb very close to the slit, so that the slightest touch of the R.A. slow motion will keep it on the slit. For drawing sunspots, etc., it is excellent and I would not now be without it.

The drawing only shows essentials, and almost explains itself.

S is a piece of spring steel attached to the R.A. worm wheel and coming away tangentially from it at point marked with an arrow.

L is a bell-crank lever, made of a triangular piece of wood for rigidity and simplicity, and pivots on the fulcrum at *F*.

The piece of spring steel is attached to one arm, and to the other is a wooden rod *P*.

At *R* is fitted a short rack, about 2 inches long, with teeth to suit the spring wheel of an ordinary common alarm clock, which has been denuded of its face and hands, case, etc., *C*.

W is a weight to drive the telescope.

It will be noted that the clock is not required to drive the telescope, but only to control the rate of fall of the weight *W*. Therefore the weight *W* may be of ample proportions easily to drive the telescope and any accessories attached. This is a great feature, as I find I can add cameras, spectroscopes, projection screen and all sorts of accessories and the drive still continues regularly. Moreover, the regularity of the drive does not depend in any way upon the accuracy of the cutting of the worm wheel and screw, but only on the speed of the periphery of the spring wheel of the clock. These cheap American clocks are really very accurately made by most perfect machinery and, seeing that the seconds' hand travels round its dial regularly, it follows that the rate of the spring wheel must be at least as regular.

The relative lengths of the arms of the bell-crank lever must be proportional to the peripheral speed of the spring wheel of the clock, or rather that of the pitch circle, and that necessary for the R.A. worm wheel of the equatorial head and a small amount of adjustment is provided by the clock regulator.

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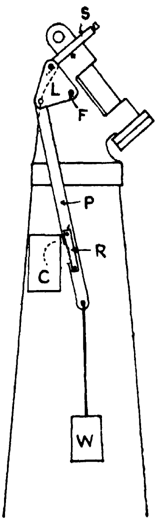
* Reprinted by permission from the *Journal of the British Astronomical Association*, April 1930.

The rack *R* can be quite easily cut from a piece of brass or aluminum; slight nicks being first made with a file at carefully marked intervals, equal to the pitch of the clock wheel. Hacksaw cuts are then made at each nick and the teeth then shaped with a small file. Only one tooth is really in action at a time, so that the exact shape is not so important as, at first sight, appears to be necessary; moreover, if the rack is cut in aluminum, which I recommend, it is softer than brass and more easily worked and very soon wears down to correct bearing on the teeth of the clock wheel. I found that



the performance rapidly improved during the first 30 or 40 hours and I still further improved it by carefully easing off the places on the teeth of the rack where, by the marking, they appeared to have been bearing too hard on those of the clock wheel.

The arms of the bell-crank lever must be at 90° to the face of the R.A. wheel (that is, parallel to the polar axis) and to the rod *P*, respectively, at the center of the travel. The angular motion of one arm compensates for that of the other, almost exactly when they are equal, and approximately in any case.

The telescope must be balanced so as to pull slightly against the weight *W*.

The R.A. slow motion is superimposed on the clock drive and to free the telescope in R.A. the worm must be lifted out of gear and a hook may generally easily be arranged to hold it out.

If required, the whole clock drive can be removed in a few seconds by removing the fulcrum screw F and taking away the rod, bell-crank, spring steel S and weight W.

[EDITOR'S NOTE: Mr. Sellers' description, reprinted above, was originally published in 1930. In 1932, two years later, the author stated in a letter that he was "still using this clock drive with undiminished satisfaction," which is presumptive evidence that it is a success.]

A water clock (clypsydra) drive made by Harold A. Lower. Water is confined within a horizontal cylinder having a piston which is connected to a weight by means of a picture cord passing over a sheave on the polar axis. A needle valve controls the rate of escape of the water. This drive has proved satisfactory for visual observation but not for long-exposure photography. Brass cylinder highly polished; brass piston with cup leather (no rings) loose enough to move of its own weight when turned to vertical position; radio vernier control on valve, and dirt screen over it. As shown here the device was removed from its customary position north of pier to permit photographing the apparatus.

Part XI.

Miscellany

By ALBERT G. INGALLS
Associate Editor, Scientific American

It would be remarkable, indeed, if the beginner did not occasionally "strike a snag." Sometimes troubles arise over little points which seem obvious to the expert. The remaining part of the book, then, is a miscellaneous collection of odds and ends, some of which it is hoped will prove useful.

What is meant by a one-third stroke? Answer: When the upper disk overhangs the lower by (roughly) one-sixth of its diameter at either end of the stroke. Thus, for a six-inch mirror, come at each end to an overhang of about an inch—not two inches. But in rough grinding, as Ellison says (Part II, Chap. II), the stroke may be much longer. Too long a stroke will probably hyperbolize the mirror.

Why can I not seem to avoid getting scratches on my mirror during fine grinding? Answer: Perhaps you have mixed a little coarse carborundum with finer sizes. Don't run your finger into a coarse size before a fine size. If necessary to do this, do it afterwards. Keep the can closed when not in use, and put it away upside down, thus keeping dust and grit out of the crack around its cover. Tack a few newspapers on the ceiling over your work, otherwise, people walking about upstairs will keep jarring down grit from the joists above you. Again, you may have previously wiped coarse carborundum on your working clothes and transferred it to your mirror several days later, during the finer stages of grinding. It is better to keep finer sizes—and rough also—in a clean wooden box, turned on its side. This keeps out the falling grit. It is a great temptation while polishing to watch the surface of the mirror from time to time. Whenever this is done, do not *rub* the surface dry, for this is a fruitful source of scratches; *blot* the surface with cloth or paper towel.

Scratches on the mirror do very little actual harm, since they cut off only a small fraction of the light, but they make the job look mussy. You will be more proud of your workmanship if your mirror is free from them. To insure this, one must be very painstaking, often to the point of seeming fussiness.

Prisms are preferable to silvered flats for small telescopes for they have no silvered surface to care for and renew. "For those who nevertheless wish to make a diagonal, the easiest way," writes R. W. Porter, "is to select a fairly flat piece of commercial plate glass. A piece of broken windshield, picked up at a repair garage, will do. Slight departures from an optically flat surface are relatively unimportant so near the focus. Another way is to figure the surface by fine grinding three small disks of glass on each other—1 on 2, 2 on 3, 3 on 1, etc.—and then polishing each disk separately. Test them by noting the interference fringes produced by pressing two of

the surfaces together. If the fringes are straight, the surfaces are flat; if they are curved, the surfaces are either convex or concave. In order to see these fringes, view the surfaces in a dark room, under the flame of an alcohol lamp, on which ordinary table salt has been sprinkled, or throw a pinch of salt on the burner of a gas stove. If all three disks, tried in all three combinations, show straight fringes, they are all flat. If they show one of Newton's rings, they are curved 1/100,000 of an inch; if two rings, 1/50,000 of an inch. The faces of one's prisms may also be tested for flatness in this manner, by laying the prism on one of these glass flats and observing the fringes. To test the right-angle, hold the prism in front of your eye, about a foot away, with the hypothenuse side facing you. Observe the reflection of the pupil of your eye. If the angle of the prism is just 90°, it will be perfectly round. If it is not 90°, the pupil will be elongated or the reverse, depending on whether the angle is greater or less than 90°."

How can I tell when the fine grinding is finished? Answer: Whittle a wedge, three inches long and 5/8 inch thick. Lay it on the mirror, hold the latter in line between the eye and an electric light placed a foot or two farther away. Then slowly lower the mirror, keeping it horizontal. If the red image of the filament remains visible on the mirror until you can sight down the slant of the wedge (that is, at about a 12-degree angle), you can begin polishing—provided no larger pits than the average size remain.

Is it worth while to finish fine grinding with emery? Answer: The writer finds it decidedly so. The polishing is done in much less time than the rules called for. Emery, like carborundum, makes pits, but they are shallower. The emery is used exactly as the carborundum is used. Every minute's work with emery pays fine dividends in time saved during polishing, later on.

Why is my pitch lap all speckled over with little bubble holes? Answer: The pitch was probably boiled and the bubbles that arose from the bottom did not escape from it. Do not heat it so fast.

Is pitch very inflammable? Answer: Take a match and try a small piece. During the melting of pitch, it is well to have a pot cover handy, to clap on in case of fire.

For the first few minutes after I begin my daily polishing, the pitch lap acts as if possessed of pure cussedness, gripping the mirror suddenly and letting go unexpectedly. No two strokes are alike, nor are they even. Answer: Have you cold pressed the lap, as explained in Part II, Chap. IV? If so, and if the "acting up" persists after a few strokes, stop and cold-press again. Pitch laps usually act this way at first while still cool, even if they are made right. They may soon settle down to business, if the pitch is not too hard. In all cases, however, the "bad acting" may indicate poor contact. This is a point about which it is hard to be definite. Whatever you do, avoid haste, and think the matter out. In cold pressing, use 10 or 15 pounds weight.

"Keeping good contact is the secret of avoiding zones," Mr. Porter adds to the above. "Whenever the glass is removed from the lap, evaporation

takes place, lowering the temperature of the lap and altering its shape. Moral: Have patience to polish for long intervals, and *always* cold press after exposing the lap. I have often safely left my glass on the lap, between polishings, for a day or so, simply by swathing it in wet compresses and covering with an inverted pan to retard evaporation, watching it from time to time to see that the rags do not go dry. After these intervals, the glass is always found in perfect contact, giving the operator by tne feel of the stroke a sense of assurance that every part of the lap is doing its work."

How shall I get the handle off the mirror without danger of breaking it? Answer: Pitch is quite strong except under sudden shock. Hit the handle a smart, sidewise rap with the screw driver handle. It will fly off without danger of breaking the speculum. The back of the glass may then be scraped and cleaned with turpentine.

What if I drop my mirror and break it? Answer: Get another glass disk. One is enough. Turn the tool over, beginning again with the flat side, and place it on a ring of pasteboard, in order to insure steadiness. Your second job will go ahead altogether faster than the first one, thus giving you so much assurance that you will be almost glad you broke the first. This, at least, was the writer's experience with his first speculum, and it will also be the case if you make more than one telescope.

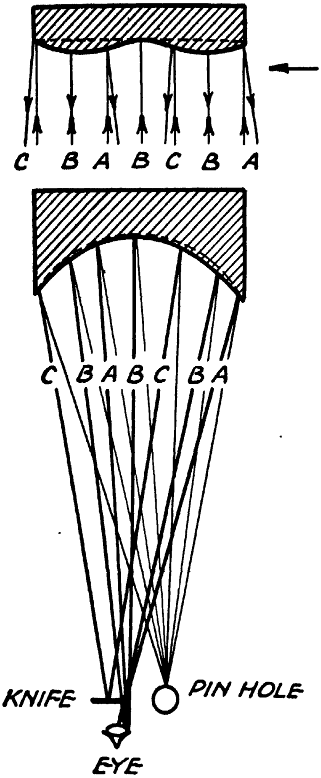
To keep well-meaning, but damaging, hands off the mirror and tool during your absence, buy a cheap galvanized water pail, remove its bail, bend the two "ears" out at right angles, invert the pail over the work, and "lock" it down by means of two short, thick screws. This excludes dust, as well as children and house-cleaning enthusiasts.

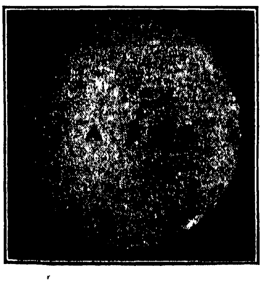
Instead of a shallow basin in which to rinse the cotton swab, try a tall container of some kind. The grit freed from the swab will then settle to the bottom, where it will stay. Thus you get practically clean rinse water each time. For example, the writer used the central container of the ice-cream freezer, which is admirably shaped for this purpose, until found out and reprimanded! A clean, tall crock is also excellent.

When you begin polishing with rouge, you will need some kind of an "all-over" garment, covering the sleeves, of course. Otherwise, rouge will stain your clothing in spite of any and all efforts at cleanliness. A linen duster is excellent. It is well, however, not to wear it during the grinding with carborundum—unless it is washed before the polishing begins. This is because grit may be easily transferred to a finely polished surface by means of the clothing.

If an electric lamp is used for the knife-edge test it must either be one with a frosted bulb, or the bulb must be frosted by the user. If an attempt is made to use it without first frosting it the result will be, not an evenly distributed diffused illumination but a sharp inverted image of the filament thrown on the mirror, much as in the case of a pinhole camera.

In pouring melted pitch on the tool, wrap a wetted strip of paper twice around it for a temporary retaining wall, fastening the ends with a daub





THE PARABOLOIDAL SHADOW

The accompanying illustration may explain the peculiar distribution of lights and shadows that is characteristic of a paraboloidal mirror with the knife-edge at its mean center of curvature (when the lights and shadows on either half of the mirror balance in respective areas). Under these conditions the mirror has the appearance of being illuminated from the side (see arrow), and of having a ring-like bulge. At bottom is a shadow of this sort, with letters corresponding to those of the apparent cross-section at top. In testing a spherical mirror we saw that the reflected rays all converged as radii to the eye and made the concave disk look flat. Such a spherical curve is dotted in behind the parabola in the central figure. The parabola touches this curve at only three places. In between, and between the curves, are two narrow strips and it is to the effect produced by these strips that we can credit our shadows. As the concavity of the mirror is actually very slight, we shall straighten out these strips and then their analogy with the bulge of the top figure will be obvious. Thin as they are on the mirror itself, these strips alter the direction of the reflected rays by a few thousandths of an inch along the axis of the mirror, and thus they may be thought of as long "pointers." For example, at eight feet the minute changes in curvature are multiplied, in effect, many times. Therefore, rays A, A, enter the eye, and the areas from which they are reflected are bright. Rays marked C are swung slightly to the left, striking the knife-edge, hence, their areas are dark. But rays marked B, graze the knife-edge and the areas from which they are reflected appear gray. In practice we make use of this parabolic shadow only in order to make sure that the curve is an evenly flowing one, for the amount of parabolizing is determined by diaphragming out all but the center and margin, as explained by Ellison and Porter.

of hot pitch (string is unnecessary). While it is still damp, and after the pitch has partly "set," strip it off.

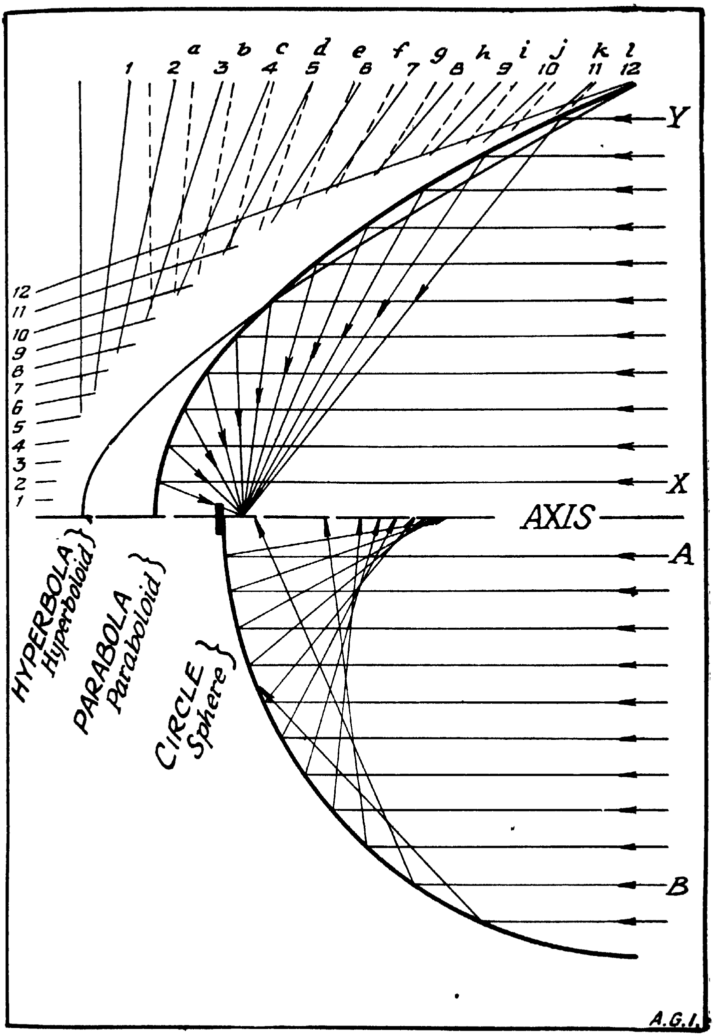
If you want to make a ten or a twelve-inch mirror, at least make a six-inch first. Old hands have plenty of trouble with these larger sizes and they are therefore not the place to get one's first experience. Above a twelve-inch, special glass is necessary, that being a sort of critical or limiting size with regard to warping, distortion, and so on. A larger size than sixteen inches will require more elbow grease for the polishing than one man usually possesses.

Those who are not familiar with the conic sections (See Figure 15, Part I) may find the accompanying drawing a help in visualizing some of the curves. Here they are purposely exaggerated. A correctly figured speculum has the form of a paraboloid, the surface which is generated when a parabola is revolved about its axis through 360°. This is the only existing curve which will reflect the parallel rays of light arriving from a distant object, to a single point, called the focus. As we saw in Parts I. and II., the proper way to bring the surface of a speculum to a paraboloid is first to bring it to a sphere, and then very slightly to deepen the central portions of this sphere into a paraboloid.

We might even remain satisfied to leave it as a sphere, or still less useful, as a mere approximation of a sphere, and this is the method (described in Part VII) for those who cannot master the more exacting but intensely interesting process of parabolizing. A sphere will not, however, reflect the rays to a perfect focus. This is shown clearly, although in an extremely exaggerated form, in the lower half of the diagram shown. Here, as in all similar cases, the rays that strike the mirror at different parts of its curve are reflected away again at the same angle, just as a billiard ball without spin bounds away from the cushion at the same angle as that of its approach.

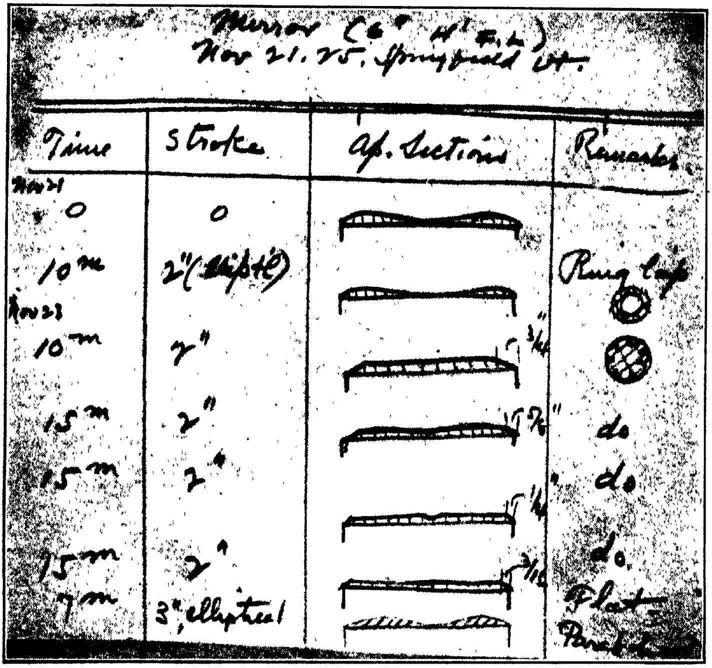
Now our six-inch speculum, having an eight-foot radius or center of curvature, must be thought of as a very small part of a great hemisphere of that radius, and if it were possible to make such a mammoth hemispherical speculum (see lower half of cut), then the ray B, striking near its outer *edge,* would be reflected to that point on the axis of this hemisphere shown by the arrow; the ray A, striking near the *center,* would be reflected so as to intercept the axis about three feet forward of this point, while the other rays would fall between these extremes. Therefore our focus would not be at a single point, as is desirable, but along the axis.

Since, however, our speculum (indicated to exact scale, in solid black) is only six inches in diameter, it occupies only a small fraction of this hemisphere, and that part is close to the axis. Therefore the rays reflected from this shallow curve will be found to cross the axis so closely together (note rapidly decreasing spaces between reflected arrow of B, and that of A) that the definition of the telescope will not appear to be seriously injured—at least until the beginner, after some hours or evenings of observing, develops a taste for better things. Hence some have recommended the omission of parabolizing, calling it quits when a sphere has been attained. However, the worker who can make a good sphere (not easy) can surely make a parabola.



THREE COMMON CURVES. FOR EXPLANATION, SEE OPPOSITE PAGE.

The upper half of the diagram referred to, shows how parallel arriving rays are reflected from a paraboloid, which is a curve whose radius, unlike that of a sphere, shortens continually as the axis is approached. Here again the angle of reflection of each ray is the same as the angle of incidence, but



A SAMPLE RECORD OF WORK

It shows how a hyperbolized mirror with turned-down edge, due to use of too long a stroke, was treated and brought to rights. Such a record should be kept from the very beginning. It will prove invaluable in making the next and larger mirror.

the changing radius of curvature of a paraboloid compensates for this and brings all of the rays exactly to a single point—the focus.

The hyperboloid is still deeper than the paraboloid, having a shorter radius at the vertex. It does not bring the reflected rays to a single point, although for the sake of avoiding confusion the reflected rays were omitted from the drawing.

Regarded from the aspect of the making of specula, these three curves should be shaped so that they all start together at the vertex and cross each other at the edge of the speculum. To have done this here would, however, have added confusion to the drawing. If one has time, it is well worth while to hunt up one's dusty school books and lay out a curve of each type. Enough of the working lines were purposely left or indicated, so that the student can reconstruct the method, by prolonging them until they cross. There is a set for each curve, based on equal divisions of unequal spaces, horizontal and vertical.

"The two arms of a parabola are more nearly parallel as the distance to the right increases, and approach parallelism as the distance to the right approaches infinity. If the arms of the parabola are opened out so that they are no longer ultimately parallel, we get the hyperbola."—MOULTON.

It is advisable to keep a systematic record of one's spells of grinding, polishing, and especially of figuring, for such a record will prove invaluable if a larger mirror is attempted later, as is likely. A typical record showing how a hyperbolized mirror was remedied, is shown on the previous page, not only as a sample but in order to show how an expert "doctored" a mirror which was brought to him with a hyperbolic figure and a turned-down edge, both of which had resulted from the use of too long a stroke in fine grinding.

The first line of the record shows an apparent section like that described in Part I, Ch. I (hyperbola). The center was now shaved away from a pitch lap, leaving a ring, and an effort was made with this tool to move the ridge of the apparent cross-section farther toward the center, using an elliptical stroke. This proved unsatisfactory, so it was decided to bring the mirror to a sphere and parabolize from that. With a pitch tool pared like the one shown in Part II, Ch. 5, and using a two-inch, elliptical stroke, the surface was gradually planed down to an apparently flat plateau (sphere), leaving, however, the turned-down edge. More planing narrowed this edge until it, too, disappeared. (Note that a central pit developed and disappeared again during this process.)

Finally when the mirror was spherical practically all over, it was parabolized in only seven minutes, using a three-inch, elliptical stroke. (Here the stroke was lengthened for it was *desired* to deepen the curve.) Only an old hand should attempt to go ahead and parabolize in so short a time, or in a single spell, without frequent testing.

"While many amateurs advocate coating their laps with beeswax or paraffin, or mixing these with the pitch, it is a significant fact," says Porter, "that Brashear, whose establishment has produced most of the finest optical surfaces in this country, used nothing but plain (strained) pitch.

Cloth laps are sometimes used. Felt or broadcloth is cemented to the glass tool with hot pitch and is pressed into shape with the speculum. Polishing is done with rouge and water as usual. But the surface produced in this manner is never as good as that produced by pitch; it is slightly wavy. The poorest work of this kind is called by the mirror-working fraternity, 'a lemon-peel finish.' Pitch starts in work by *shearing* off the tops of the irregular elevations left by the fine grinding; the valleys between are

not touched until, at the last, they—that is, the few remaining pits—vanish as if by magic. It is estimated that any effort to bring a surface nearer to perfection than a quarter of a wave-length of light, viz., 1/200,000 of an inch, is time wasted. This amount—five millionths of an inch—is just detectable with the knife-edge test."

Do not swab off the mirror with waste, for this is generally full of sharp grit. A two-ounce roll of absorbent cotton—a standard drug-store size—can be cut into a number of four-inch lengths, and if each length is rolled up separately in paper, and kept rolled up until needed, it will be free from grit. Paper towels used like blotters are also excellent for cleaning the mirror.

Melted pitch will not strain through muslin. Use cheese cloth, and double it once or twice. This removes any grit that may be in the pitch.

Attach a long stick of wood loosely to one end of the rack on which you place the mirror during the knife-edge tests. This will enable you to control its position from the testing position several feet away, an invaluable aid.

Soon after rouge polishing begins, the Foucault shadows may be seen.

Sometime, while testing the speculum, lightly place the finger tips on its face for a few seconds. When quickly viewed from the knife-edge position, the "hills" due to expansion under your warm finger-tips will all stand up sharply. This trick always impresses visitors with the delicacy of the Foucault test. Also, have someone hold his hand below and near the speculum while it is in the testing rack: the waving currents of air due to the heat of the hand are a revelation!

Experts advise keeping the eye very close to the knife-edge during testing, even removing one's eye-glasses—provided it is possible to see without them. To discover why the eye must be kept close, first place it close, then move it slowly back; the mirror apparently becomes covered with black radial streaks. This is an unavoidable condition existing in the human eye itself.

If the grinding stand is not quite level, no harm will result: you will always get a perfect figure of revolution, because you keep turning the tool and the mirror around from time to time by varying amounts.

It is convenient to keep the coarser sizes of carborundum in a large, cleaned salt-cellar; the finer sizes may be made up into a cream before using.

While Porter advises the use of sizes 80, 120, 280, 400 and 600 carborundum, Ellison recommends sizes 80, 200 FFF, 400, 500 and 600. While these seem contradictory, what we have in both cases is simply a series of grains regularly diminishing in size. Either group is equally suitable.

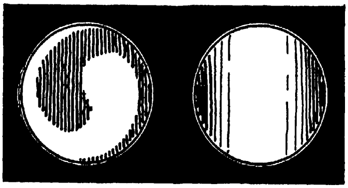
Unlike common "looking glass" mirrors, it is the face (concave) of the telescope mirror which is to be silvered.

The sharp edge produced in case the disk becomes ground down excessively is liable to chip off and scratch the mirror. Hone or chamfer this edge off with a carborundum stone, washing the mirror thoroughly afterwards.

Should the disks become stuck together, try a wooden mallet. A hardwood lever with chisel-shaped end, inserted at edge notch, and pried carefully over a fulcrum, may lift the mirror. If necessary, melt out the pitch in water warmed and heated very slowly and make a new lap.

The following 56 pages of the Miscellany consist of notes prepared for the second edition two years after the previous notes were written. Many of these new notes have been directly inspired by requests for help made by other amateurs; also by practical difficulties encountered by The Editor in his own work. Abstracts and extracts from scattered and often obscure books and articles bearing on telescope making follow later, and it is hoped that some of these will prove useful to the advanced amateur who wishes to explore beyond the beaten path.

Warped Mirror: The shadowgraph characteristic of a warped or "twisted" paraboloidal surface is similar to the emblem of the Northern Pacific Railroad, known as the "monad." A mirror showing this figure persistently should, according to Porter, be treated as follows: Seek out a good hard, solid hydrant. Hurl the mirror as fiercely as possible at said hydrant. Walk home. Such a



DISTORTED MIRRORS

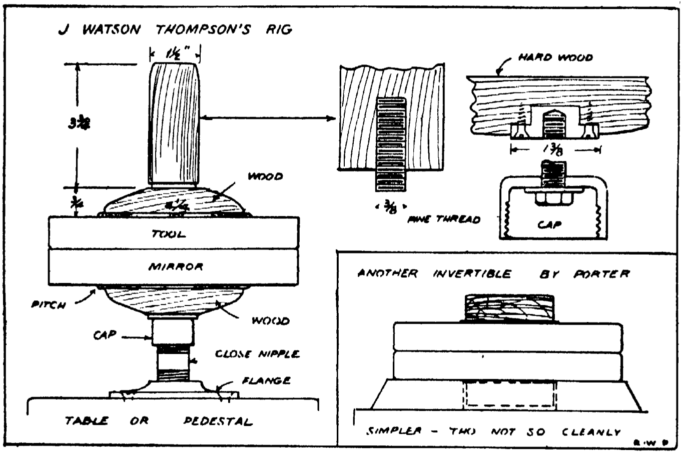
mirror is strained and is hopeless; the glass was not well annealed.

A high and wide separation of knife-edge from pinhole will produce a monad shadow.

Astigmatized Mirror: Suppose the shadow comes in from both sides at once, making two half moons of deep shadow, one on either side. This indicates that the mirror is no longer a figure of revolution but an oval; it has astigmatism. One must go back to fine grinding again, then polish a few minutes and test. If it still shows oval, the chances are that there is a weak diameter, the glass was badly annealed and the disk is hopeless. Only one case of this kind of tragedy is known to The Editor, so far.

Needless Efforts: There is no need of making a slavish duty of "walking around the barrel" while grinding and polishing. One may safely stop in one place and take 10 or 20 strokes. Because one does not then have to think of constantly shifting, more pressure can usually be brought to bear on the disk and excavation will be accomplished in proportion. There is no danger of getting the curve lop-sided by this method. But when it comes to polishing, this method will usually give a surface which under knife-edge test appears lumpy, like that of a "dog biscuit." Therefore, just before getting ready to test, taper off by taking successive groups of, say, 8, 4, 2 and 1 strokes in a place. This will even up the surface. There is no objection to sitting down to work, provided the tool be turned a little now and then.

Inverting Tool and Mirror: In grinding, Ellison gives instructions to allot to certain sizes of carbo. certain reductions in length of radius. An alternate method is to employ a rig which will permit quick inversion of mirror and tool—*i.e.*, tool either on top or on bottom, at will—and then excavate all the way to ultimate radius with the first size of abrasive. From then on one may hover more or less around that radius by alternately inverting and re-inverting. This also brings plenty of work on the outside zone of the mirror, which ordinarily polishes out last and, therefore, needs it. With this method, however, one must be on the watch for turned edge, due often to the application of force too high up on the handle. As finer sizes are used, make the simple pencil mark test for sphericity, by carefully drying and cleaning the tool and mirror,



INVERTING DEVICES

It is a marked convenience to be able to invert tool and mirror, and without time-consuming bother

drawing pencil marks across each, working them dry with a few very short strokes and observing where they are in contact by noting where the marks are rubbed thin or entirely off. To get rid of the turned edge, which probably amounts, when noted at this early stage, to what would be considered grossly and incurably turned if permitted to pass on to the polishing stage, remove the handle and grind a few wets with strokes less than one inch long. It is well, if this more elastic method of reaching the desired radius by inverting tool and mirror is employed, to arrange to leave an inch or less of radius at the end for polishing, and to do most of the polishing right side up, thereby avoiding possible turned edge from that source and perhaps facilitating the observation of

contact with lap by permitting the worker to look through the glass while polishing is in progress.

Inverting Device: For those who really enjoy elaborating the few simple tools needed for telescope making, a rig for hand grinding and polishing, made by J. Watson Thompson and presented to The Editor, may be constructed—provided one has a lathe. This has proved entirely satisfactory and most convenient when it was desired to invert the normal positions of the tool and mirror. The sketch explains it. It also has the additional advantage of keeping the work up out of harm due to grit from the usual bench or pedestal. A common pan with a hole cut through the bottom for the stem of the stand is

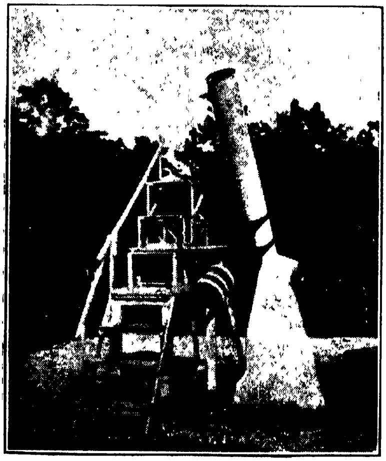
A HOME MADE TELESCOPE

Made by Professor George H. Hamilton of Jamaica (note low angle of polar axis, for use in 18° N. Latitude). The owner also made a 12 inch, and has commenced a 21 inch. Described in the Scientific American, January, 1928, pages 46-47.

usually placed under it. This catches all drippings and can be cleaned up in a jiffy. Another advantage this rig embodies is variable height—obtainable by inserting pipe nips of various lengths in the upright stem. The wooden flanges shown in the drawing are a slight variation of Thompson's original job, in which disks only about 2 inches in diameter were used. These do not "blindfold" the mirror while it is being worked (you can see the contact through it), but they did not, at least in one man's hands, provide enough area to keep the disk from breaking off under stress of hard work.

Sticking Mirror: Bubbles that form between mirror and tool may be pushed

out if one wishes, simply by sliding the top disk away out over the lower one and then carefully drawing it back; then the same on opposite side. Occasionally a mirror will stick and suck, even during fine grinding. If the disks are spherical and have an equal radius they will not stick (although any mirror ought to push a little harder as it passes over the other, for more surface is in contact at that part of the stroke). If the disks stick they may be badly hyperbolic. If the latter, they cannot make good contact at ends of strokes, there is a tendency to create a vacuum between them, and this will account for the sticking. A very short stroke—sometimes less than an inch long—will usually doctor any such condition in a few minutes. "Or," Porter states, "one may



A GOOD OBSERVING STAND

Made by Professor George H. Hamilton. It is light and rigid. Being sectional it permits adjustment to any desired height of eyepiece. Note the overhanging shelf next the telescope. This facilitates standing close to the eyepiece.

press down locally at the *edge* of the mirror as it revolves under his hands, thus wearing away the edges of mirror and tool and bringing their central portions back again into contact."

Laps in Hot Places: In the tropics, pitch may refuse to perform well, due to the heat. Vard B. Wallace used resin tempered with beeswax while making a telescope in Guatemala. Professor George H. Hamilton of Jamaica, British West Indies, author of *Mars at Its Nearest* and the maker of two telescopes described in the *Scientific American*, January, 1928, has had considerable experience with laps in warm climates.

Uniform Working Temperature: When the advice to work in the cellar is given it is not to be inferred that one who has no cellar cannot make a telescope, provided he can find a warm workshop that stays at fairly uniform temperature—say, within 5 degrees or so. As Ellison says, it is changing, not changed, temperature that plays havoc with the job. If forced to use a warm place one must, of course, experiment with harder laps of boiled-off pitch or some of the materials suitable for the tropics.

Describing Cold Pressing, Ritchey says, "When it is sufficiently pressed the surface appears uniformly smooth and bright." Incidentally, this points out the value of keeping the back of the mirror relatively free from blindfolding obstructions, so that one can see what goes on at all stages of the polishing.

Turned-down Edge: Ritchey forestalls turned-down edge by "diminishing the area of the squares around the edge of the tool, by trimming their edges." On this, Porter comments, "It is O.K. Have done it frequently to advantage."

Substitutes for Pitch: As soon as the first edition of the present work appeared, several amateurs experimented with other substances than pitch for laps. H. L. Rogers and a co-worker coated a pitch lap with ordinary Johnson's Liquid Floor Wax, giving it two coats (very even and very thin). Rogers states that a fine polish was obtained. A variation of this was to dry the liquid wax over a gas stove. The lap and mirror were kept in a bowl, just covered with water, when not in use, thus maintaining the lap in perfect condition.

"Pitch," says Wegener in *The Origin of Continents and Oceans,* "behaves as an absolutely solid body when subjected to blows and percussions, but, given time, it begins to flow under the influence of gravity; a piece of cork cannot be forced through a sheet of pitch, but after a lengthy period its slight buoyancy is sufficient to allow it to rise slowly through the pitch from the bottom of a vessel." He goes on to observe that pitch is harder than a candle, yet if one lays a stick of pitch and a candle horizontally between two supports, the pitch will bend of its own weight while the candle will not. According to definitions given in Maxwell's *Theory of Heat* (1872), the candle is, therefore, classed as a "soft solid," while the pitch is a very "viscous fluid." For an interesting article on pitch, by F. W. Preston, see *Transactions of the Optical Society,* No. 3, 1922-1923.

Prolonged Cold Pressing: "The mirror may safely be left in contact with a pitch lap for several days if the rouge is moistened with a 50 percent solution of glycerine and water. The glycerine prevents the evaporation of the moisture, and the local humidity will govern the amount required. This suggestion is particularly valuable if one is able to polish or figure the mirror rather infrequently. While the glycerine keeps the surface of the pitch moist, the glass, by its own weight alone, will gradually make perfect contact, without unduly squeezing down the pitch and springing the glass caused by the use of weights."—B. L. Souther.

Channels in Laps: What is the purpose of cutting channels in the pitch lap? We often hear that they are for facilitating the spread of the rouge.

This is true, but there are two other and at least equally important reasons. The channels admit air, and thus break up sucking or adhesion of the mirror. But, most important of all, they permit contact to be established by cold pressure, for they provide the pitch with a place to escape to when it is slowly deformed under pressure. Without them the pitch would have to flow clear out to the edges of the tool. With this in mind, it should be apparent that shallow, half-hearted channels do not greatly facilitate good contact. Cut them

A HOME MADE TELESCOPE

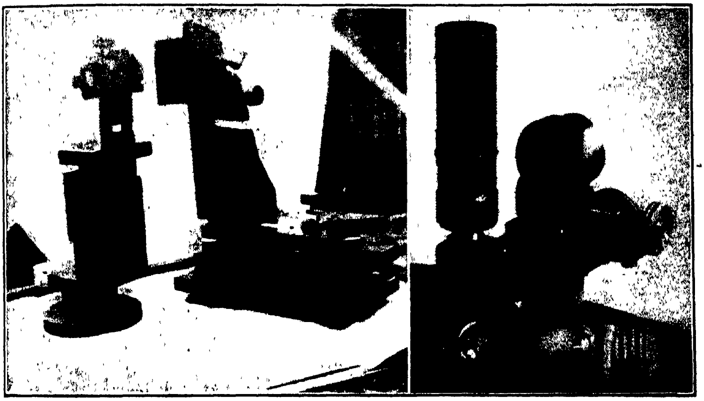
J. A. Johnson, Opt. D., made this rather unusual instrument which was described in the Scientific American, August, 1928, page 172. The mirror is a 10 inch, of 72 inch focal length. The telescope has setting circles. Study the pedestal; it contains an elaborate clock drive made by the owner. The housing of the telescope moves aside on two tracks.

down to the glass itself—they will fill in rapidly enough by slow flow, while one is working.

Test for C. of C.: Many have passed up Ellison's test for center of curvature (page 78) because it is "hard to perform," "awkward," and so on. If one will persist it will soon become simple enough, just as is the case in learning to do anything new. Used in coarse grinding, it will give the center of curvature within 8 inches, and in fine grinding, down to an inch or sometimes less. The

test is a valuable aid. An electric flash lamp is splendid for this test, but is more accurate when both the bull's-eye and the reflector are removed. Another method is to take the mirror, wet, out into the sunlight and see where the reflected disk of light (at focal plane) is least indistinct. This test, of course, gives focal length, not radius of curvature.

Tubeless Telescope: If one is forced to observe near strong street lamps, or if one wishes to use his telescope as a terrestrial instrument, the tubeless mounting described on page 28 will not function any too well, the view being somewhat fogged by the outside sources of light. It is better to employ a tube for these purposes.



SLOW MOTION DEVICES FOR TESTING

The one in the left hand photograph was made by Henry H. Mason, from a description by Rev. C. D. P. Davies, in Monthly Notices, Royal Astronomical Society, March, 1909. Hinges and thumbscrews permit motion in two planes and there is a fixed magnifying glass with which to read the scale. The lamp is also shown. The apparatus in the right hand photograph is described in the text. The annular ring takes a standard eyepiece when the eyepiece test is to be made. The knife-edge is attached to it merely by wax and may then be removed. Apparatus of the kind shown in these photographs is not required, but some enjoy constructing it and it is useful.

Electric Lamp for Knife-edge Test: Page 7 gives a hint that an electric lamp will prove suitable in place of the hot, smoky, cumbersome old-fashioned kerosene lamp for this test. Several years ago a practicable method was found —and a most simple one at that—by J. Watson Thompson, a lawyer. He simply frosted the lamp bulb with carbo. The resultant illumination through the pinhole was perfectly uniform when seen on the mirror. It would be well, however, to see to it that the pinhole does not come quite opposite the actual filament of the lamp. A 110-volt, cylindrical candelabrum lamp bulb about an inch in diameter was employed, having straight sides and a miniature base. The

lamp is easily frosted by daubing it with No. 220 carbo., wrapping around it a strip of thin sheet metal and working it in the hand a few minutes. By purchasing an "adapter" the miniature base may be made to fit standard lamp sockets. One may fill in the "throat" left around the base of the lamp with plaster of Paris, in order to hold the bulb more firmly. This bulb is simply introduced from above into a piece of tubing perforated for the pinhole. It is a great convenience thus to do away with the mussy oil lamp. In localities where the voltage is a bit high the lamps may burn out very quickly. This is because they become too hot in their prison, electric lamps being designed for a normal amount of air cooling which they do not get when inside of the tube. Here it may become necessary to insert a small resistance in series into the line, to ease off the voltage a little bit. The new inside frosted electric lamp bulbs can be used to almost equal advantage.

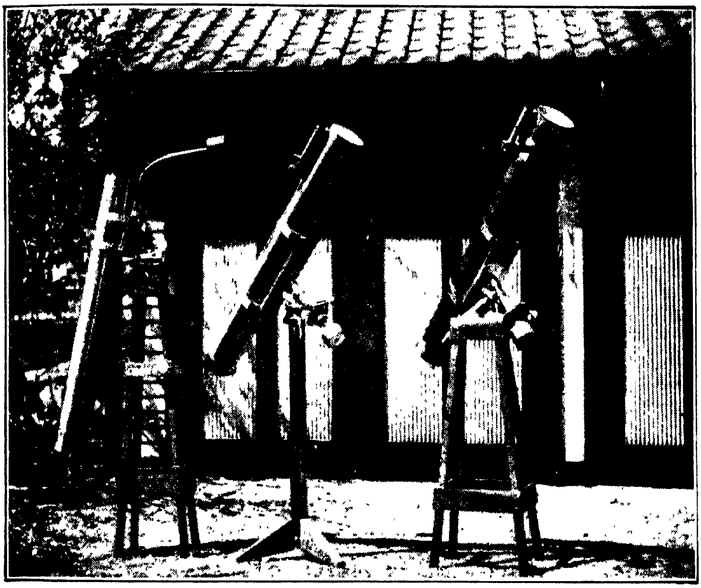
Tiny Pinhole for Advanced Workers: Prof. Ritchey says: "When the knife-edge test is used with an extremely small pinhole of between 1/250th and 1/500th of an inch in diameter, illuminated by acetylene, or what is much better, oxy-hydrogen or electric arc light, minute zonal irregularities are strongly and brilliantly shown, which are entirely invisible with large pinhole or insufficient illumination."

Sleeks (minute patterns of scratches visible only in favorable light and at certain angles) may often be removed by a few moments' polishing on the dry lap. Another method is to start polishing on them with short strokes and scarcely any rouge, and gradually increase stroke and amount of rouge.

Avoiding Scratches: Newspapers are cheap and can be used to good advantage to prevent scratches on the mirror. One may lay or tack them on tables and all places likely to harbor coarse grains of abrasive, and then tear off a page or two with each change to finer abrasive. It is well to be fussy about not getting carbo. on tool handles, etc., from which a few coarse grains may easily be picked up later on. Any rag or towel that may be used as a general sop-up around the shop is a likely culprit. Ordinary cotton waste is safe for swabs only during coarse grinding but not for fine grinding, as it often contains grit. Here it is best to use absorbent cotton (see page 286 near top). For drying mirrors The Editor uses paper towels or a handkerchief. In favor of the latter is the fact that the same handkerchief is not likely to be in one's pocket long enough between trips to the tub to carry coarse grit over to the next finer stage of grinding. Worst of all habits is that of wiping one's hands on one's work clothes, for these are usually worn throughout several stages of finer and finer grinding. Old hands at mirror making appear careless about grit. This is an "optical illusion"—they know just when and just where they can get away with it without risk of scratches. Until one has become wise it is better to play safe and be fussy.

If one has reached the last stages of fine grinding and is worried about scratches, it is just as well not to start off each new wet with a long stroke, for if any coarse particles were present this would drag them clear across the mirror. But a group of very short strokes will at least localize such scratches and the offending coarse particle will generally be broken down quite quickly.

Even this is, however, a botch or makeshift and contaminated carbo. should really be washed. Transfer it to a common drinking glass (clean), stir it up and observe how fast it settles. As the heavier particles are to be sorted out by taking advantage of the fact that they settle more rapidly, we strive to pour off or syphon off the water into a second glass after the right lapse of time, leaving behind any coarse particles. A bit of preliminary experimenting with this process will teach more than a ream of words.



THREE HOME MADE TELESCOPES

Made by H. L. Rogers and described in the Scientific American, November, 1926, page 373 and November, 1927, pages 468-469. The one in the center shows the ingenious finder described elsewhere in the present volume Rogers became interested in the work when Amateur Telescope Making was first published, and since that time has made a number of telescopes.

How Long Is a Wet? In grinding, the best test for the proper length of a wet is when the grit stops sounding gritty. If one is of an investigative turn of mind and has a medium-powered microscope it is interesting to start with a charge of fresh carbo., grind 20 or 30 strokes and examine a dab of the charge under magnification, noting how the grains have broken down and how many particles of glass are commingled with the abrasive. Carry this out until the

carbo. is all broken down and glass predominates. It will prove instructive and worth while.

Fine Finishing Abrasives: By means of abrasives finer than No. 600 Carbo, used before polishing proper is begun, the polishing period may be shortened. The American Optical Company's M 301, M 302, M 302½, M 303, and M 303½; the Norton Company's E 108 (super-finishing); The Bausch and Lomb Optical Company's 902½, 903, 904 and 906—all are suitable for the purpose. They may be used either on glass, pitch (p.80) or HCF, but preferably on pitch or HCF. On glass they will grind, on pitch or HFC polish, and it is a question whether the final goal will be sooner reached if thus preceded by very fine grinding or by coarse polishing. An underlying principle is this: On glass—that is, an unyielding backing—abrasives, coarse or fine, will grind, that is, crush or splinter (pp. 326, 329); even rouge will not polish between glass and glass. On pitch or HCF—that is, a yielding backing—abrasives, coarse or fine, will polish, that is, minutely scour or plane (p. 329); a piece of wood charged with Carbo, even if coarse, will give a kind of polish but will not grind. Hence, to obtain a pre-polish, either charge a pitch lap with finishing abrasive or rub a scrap of HCF over the glass tool, so that the lap will not skid, lay on a sheet of HCF, then the mirror, cut around the HCF, and add one or two tablespoonsful of thin cream (thick will accomplish less) made from some of the fine abrasives—for example, M 303½. This should last through the one hour of work which is recommended. Later, polish with rouge on another pitch or HCF lap. A further refinement is to follow the 303½ with a half hour or so of Levigated Alumina (made by the Norton Company and nicknamed "Levigal" by Uncle Ephram, because Levigated Alumina is a mouthful) or to use Levigal alone as the prepolishing agent. This abrasive, which does not stain, is not white "rouge," as some have called it, and is composed of Al_2O_3. It is much finer than the others—only 2 to 4 times the size of ordinary rouge particles, according to Dr. S. H. Sheib, a Richmond amateur who measured its grains.

Correcting a Hyperbola: Working with a pitch lap, H. L. Rogers states that he has successfully reduced a hyperbola, simply by painting a ring of rouge on the outside inch or so of the tool, keeping the remainder of the tool just wet enough to slide nicely, and using short strokes.

Chamfering of Disks: Sometimes the disks when received are not chamfered on the edges, and sometimes one will quite wear away the chamfer, leaving a sharp, delicate edge. This edge is liable to chip off and the chips are more than likely to scratch the surface. Accordingly, the business edges of both disks should be honed with a carborundum stone held at an angle. In the average case The Editor finds that a bevel carried one-sixteenth inch back from the edge will nearly but not quite grind out—for we wish to leave a small width of bevel on the finished job. It is not so well, however, to put off chamfering until later, for tiny round chips are likely to be flaked off from the surface near the bevel, and polishing or even fine grinding will not excavate enough

glass at the edge of the disk to work them out. It is best to do the beveling at the start; and then keep an eye on it in order to increase its width if necessary before the job has progressed too far.

Thickness of Glass Removed for Each Stage: While we are plugging away with the various stages of grinding we shall want something to think about. And here is something: How much actual depth of glass does each stage of grinding ordinarily remove? And especially, how much removal of glass does polishing involve? If we know these amounts, even in round numbers, it will frequently be of use to us, improving our judgment when it comes to making certain decisions.

To arrive at these figures by calculation is easy. Knowing the radius for each stage of grinding and polishing, we simply substitute in the formula $r^2/2R$. This is none other than our old playmate, the r^2/R formula, altered a bit because here we are no longer dealing with a beam of light whose aberration is doubled by reflection (which accounts for the R, instead of 2R) but determining the actual depth of the curve with regard to a straight-edge placed across the surface of the mirror. This depth is called the "sagitta," the Latin word for arrow (the line of the sagitta perpendicular to the center of the glass resembles an arrow held on a bow).

Let us assume that we are working with a 6-inch mirror having a radius of 96 inches. Assume, also, that we reduce the radius of curvature to 132 inches with No. 60 or 80 carbo.; 22 inches more with No. 100; 10 inches more with No. 220; and about an inch more with each successive size; finally alloting a generous inch to polishing. We substitute in the formula and obtain the following figures:

Carbo. No.	*Radius*	*Substitution*	*Sagitta*	*Difference*	*Or Roughly*
60	flat to 132″	9/264	.03407″	.03407″	1/30 inch
100	132″ to 110″	9/220	.04090″	.00683″	1/100 inch
220	110″ to 100″	9/200	.04500″	.00410″	1/250 inch
280	100″ to 99″	9/198	.04545″	.00045″	1/3000 inch
400	99″ to 98″	9/196	.04591″	.00046″	1/3000 inch
600	98″ to 97″	9/194	.04638″	.00047″	1/3000 inch
Rouge	97″ to 96″	9/192	.04682″	.00044″	1/3000 inch

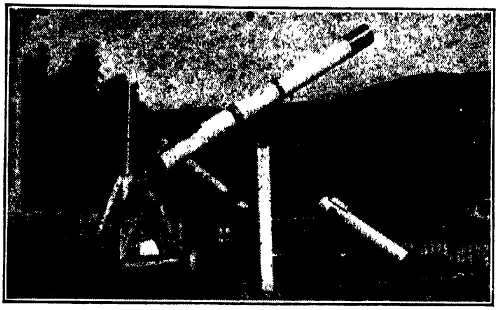
Thus we see that we have worked about as hard to excavate 1/3000 inch with one size carbo. as we did to remove 1/100 inch with another; and about five times as hard to polish off the last three-thousandth of an inch with rouge as we did to remove a whole 1/100 of an inch with carbo. As a matter of fact, these are not, strictly speaking, the actual depths of glass worn away, but rather the differences between the amounts worn away at edge and center of disk. (Probably half as much glass is worn away at the edge as at the center.) But no matter—we now have in mind a rough idea of the amounts we are dealing with for each stage of the job, and these amounts will apply in a general way to most of the mirrors we are likely to undertake.

Finally, in altering our final sphere to a paraboloid, how much do we actually scoop it out? A mere 87,000th of an inch! For the inside zone of the

parabolized mirror has about one-tenth of an inch shorter radius than the outside zone; and we may thus calculate the amount of deepening by the same formula as above.

F. W. Preston of the Research Laboratory of Messrs. Taylor, Taylor and Hobson, Ltd., states that in their workshops it is known that there is commonly removed in the polishing process from 6/100,000 to 12/100,000 of an inch in thickness. It is found, he says (*Trans. Opt. Soc.*, No. 3, 1921-22, p. 159), that with automatic polishing, and when the polisher is working at its best, this amount is removed in 50 or 60 wets. Consequently, the average amount removed per wet is in the neighborhood of one or two millionths of an inch.

In Grading Carbo. it was found by Dr. J. W. French that the grains fell through water at a velocity directly proportional to the diameter of the particles. Theory calls for a fall proportional to the square of the diameter. But many a fine theory is exploded by a mere fact. (*Trans. Opt. Soc.*, Oct., 1917, article on grading carbo.)



HOME MADE TELESCOPES

The three reflectors shown were made by Messrs. Herron and Ferguson of the "Amateur Telescope Makers of Los Angeles." See Scientific American, March, 1928, pages 244-245.

Range of Size: If rouge be left in water 10 to 15 minutes the particles remaining in suspension will have an average diameter, according to Beilby, of 1/50,000 to 1/30,000 inch. This compares roughly with the average wavelength of light. Beilby believed these particles were actually aggregates of cohering units which would probably be reduced under work to finer form. The microscope will resolve scratches made by an abrasive down to about 1/100,000 of an inch in width, unless strong dark-field illumination is employed, and a wavelength of violet light—the shortest of the visible rays—is just about 1/100,000 of an inch.

Keep a Log Book: Write down in it everything you do. It will prove invaluable on subsequent jobs, especially if they do not happen to follow closely

on the heels of the last one. It is well to jot down various "don'ts," just when the situation arises that provides the don't. Then, some months later when you tackle the next mirror you will read this record, discover your mistakes, profit by them and get off to a flying start. There is still another reason for recording everything: amateurs of the future may come to treasure your records—should you evolve into a Herschel, a Ritchey.

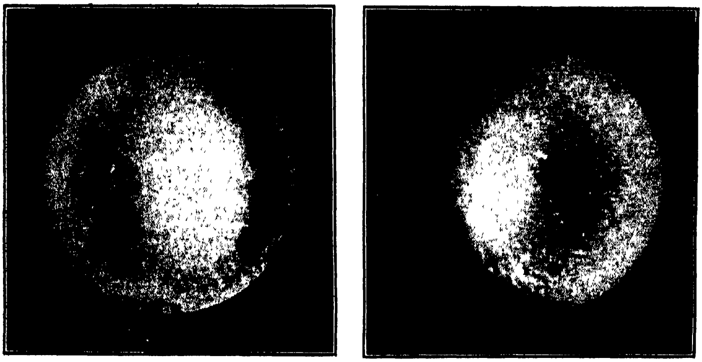
Limiting Devices: Every now and then someone devises an automatic limiting device for insuring strokes of uniform length, or one for turning the tool by some even part of the circle. These ingenious devices are worse than useless, for the very merit of hand work is that the combination of stroke length and direction is never twice repeated, thus preventing the development of zones, etc. On the other hand, no slavish effort should be made to vary the length of strokes. This will take care of itself.

Take Courage: With regard to his mirrors Ellison is exceedingly particular, and it has often been suspected that the little paragraph at the top of page 89 has been responsible for scaring off many a prospective telescope maker who did not know that a mirror may fail by quite a lot to come up to Ellison's high standard of perfection, yet function so well that the difference would not be worth the price of throwing up the sponge at the outset. Sir William Herschel's many mirrors were recently brought to light and given a knife-edge test. Some of them proved to be what a modern amateur would call "not so good." Yet they functioned passably well in use. Sir William did not have the advantage of the knife-edge test, but worked by feel alone. Foucault had not yet discovered his famous knife-edge test. If you are wavering, don't let Ellison's criterion of perfection scare you off.

Getting Contact Before Polishing: There is one place where Ellison might to advantage have been more explicit. Near the bottom of page 77 he recommends the use of the long (full) stroke for roughing out. This is good, not merely because it saves much work and time, but because it leaves the outer zone of the disk comparatively untouched while a shorter, roughing-out stroke would bring nearly as much work on the outside zone as on the center and thus take quite an appreciable total thickness off the mirror—a point which may become important if the disk is none too thick to begin with. Now, the important point is this: after the long strokes of rough grinding have scooped out the center irregularly, as Ellison says, leaving it a pronounced hyperboloid, the two disks *must* be brought back to *full* spherical contact all over before polishing begins. Preferably they should be brought nearly so before fine grinding. It has been noted that, since the first edition of the present work was published, several mirrors, when finished, proved to be very seriously over-corrected. In two cases the knife-edge test showed that the radius of the outer zone was a full inch greater than that of the inner zone, instead of about one-tenth of an inch (in the case of a 6-inch mirror of f/8). Here the assumption is fairly safe that the hyperbolization came about, not in polishing, but before fine grinding was finished, and was probably due in part to Ellison's failure to stress the point so urgently stressed above.

Watch the liquid sludge through the mirror disk while grinding. This film

of sludge looks thicker than it really is. To measure it roughly, and follow its diminution in thickness from time to time while working, wash both tool and mirror, dry them, brush them absolutely clean with the hand and place a tiny scrap of paper in the center of the tool. Usually the mirror will teeter on the paper to a noticeable extent when it, with the tool, is grasped on either side and between forefingers and thumbs. By choosing thinner paper from a book it is possible to watch the discrepancy between tool and mirror narrow down as the work continues. While a single sheet of India paper is only about one-thousandth of an inch thick, even that is quite a large departure from the spherical if one foolishly leaves it to deal with by means of rouge, whose cutting powers, quantitatively reckoned, are comparatively slight; or for that matter, even with No. 600 carbo.



PARABOLOIDAL SHADOWS

The one on the left is reproduced from the plate which accompanied Foucault's original announcement of the discovery of the knife-edge test. Foucault placed the pinhole on the left, which will account for the location of the shadows on the disk. The picture on the right is a direct focogram made by Dr. Nakamura. See the text.

A way to check up on the scrap of paper method is the pencil test (see page 288) or, safer from scratches, Kirkham's water drop test: float the dry disk on one drop of water. The separation may be easily calculated, and comes out on the general order of magnitude of a ten-thousandth inch. There is no use of proceeding with polishing if the disks are not spherical.

Correct Paraboloidal Shadow: Astrophysical Journal, June, 1918, contains an article by Porter, entitled "Knife-Edge Shadows—Photography as an Aid in Testing Mirrors." A camera was placed behind the knife-edge, at the center of curvature of a mirror, obtaining thereby beautiful focograms comparable to what one sees with the eye when making the knife-edge test, but more revealing. A similar focogram made from a 12½-inch Calver mirror of f/8

is reproduced. This was sent to The Editor by Dr. K. Nakamura, of the Astronomical Observatory of the Kyoto Imperial University, Kyoto, Japan. Dr. Nakamura, a pupil of Ellison, has produced over 45 parabolic and 80 plane mirrors of high quality. He states that when measured on 10 zones this mirror showed no aberration of more than one-hundredth of an inch. He points out what some may not wholly realize, that the judgment of a surface from the shadow requires delicate estimation. (He is speaking, of course, of really first-class mirrors—let not the doubting beginner become discouraged, for even a poor mirror will provide plenty of thrills when directed on the heavenly bodies, and a better one may be produced either the first time or after further efforts. But even the word "good" does scant justice to Dr. Nakamura's mirrors.) "The paraboloidal shadow," Dr. Nakamura continues, "cannot be judged from its position, but one must study its shape and tones of shadow."

As reproduced, the Nakamura focogram is too dark in shade, but apparently this cannot be helped. Any reader who is familiar with photo-engraving and printing may appreciate the difficulty of carrying a reproduction involving delicate, thin, wispy, gray lights and shadows through the numerous processes without deviating from the original. The distribution of lights and shadows—the facial *map* of the shadows—in this focogram is excellent, but workers who are satisfied merely to copy the tone or depth of these shadows without measuring zonal radii will almost surely over-correct.

We also reproduce the famous drawing by Foucault, which, while it makes poor pretense of depicting the subtlety of the actual shadows, does show very clearly one thing of importance, namely, that the one half of the mirror's shading is precisely the converse of that of the other (with the vertical diameter as an axis of symmetry): *i.e.*, where there is shade on the one half there is light on the other, and in exactly corresponding positions. The late Dr. Calver of England pointed this out very definitely (*English Mechanics*, Aug. 28, 1925, page 96), as does Dr. Nakamura in his letter. If one squints at the Nakamura picture with nearly closed eyelashes this complementary nature of the correct shadows will be better brought out. The manner in which the respective top and bottom horns of the respective dark and bright shadows cross one another should be got clearly in mind.

Finally, and by way of further emphasis, the following is quoted from the Reverend C. D. P. Davies (*Monthly Notices Royal Astronomical Society*, March, 1909): "The one point to be noted above all others is the exceeding delicacy of the shadow. It is impossible to insist on this feature too forcibly. In spite of what Wassell and Blacklock have written, it seems almost hopeless to impress this on the mind of the average worker, who seems to think that because the shadows come on right, he has therefore got a parabolic mirror; the inevitable result of this fallacy being that the tone of shading is in reality far too deep, and the mirror markedly, often profoundly, over-corrected. In most cases the crux of the question lies in the temptation to shirk the trouble of making a proper and effective zonal measurement apparatus and cutting out diaphragms."

Testing by Interference: In *Astrophysical Journal,* June, 1918, Professor

A. A. Michelson, the noted physicist, describes a method of correcting optical surfaces by means of interference fringes. This requires a total reflection prism, a light source, a slit and a 1/12-inch microscope objective, and gives results in hundredths of a fringe of light (1 fringe is about 1/100,000 inch).

Flexure: In one case a worker rested his tool on the heads of three nails, for a three-point, automatically-adjusted support, and the result was "a mirror that gave a triple image of the sun at the focus, with all kinds of ligaments connecting the images." Similarly, a tool, especially if thin, may flexure during cold pressing under heavy weight, as S. H. Sheib points out. "When the weight is removed, the glass tool returns to its original shape, and any work on it then cannot help but produce zones. It is well to watch the wooden board on which the tool is placed, since this may become wet and warp, bending down when cold pressing is done, but springing up when the heavy pressure is released. I use a flat steel plate. This permits me to use thin tools—half to three-quarter inch in thickness." To forestall temporary flexure after heavy cold pressing on pitch, unload mirror gradually.

Optical Glass: Many beginners find it hard to believe that some special, aristocratic variety of optical glass, perhaps made in France, is not necessary for a good telescope. This belief is hard to down. Poorly annealed plate glass is an abomination, but it has certainly not plagued the thousands of telescope makers who have worked from this book for the past two years and used it on successful telescopes. The 72-inch mirror of the great Dominion Astrophysical Observatory's reflector is made of plate glass. Why, then, do some hunt all over the world for special glass? True, on sizes above 12 inches it is time to cast around for special materials—not so much with regard to their composition as to their preparation (annealing, etc.). But the man who has got that far doubtless knows his onions already and needs no such instruction; while this note is intended for that type of beginner whose name is "Doubting Thomas." Of course, there are quartz and Pyrex, and these are still better, but the point is that there is nothing wrong with commercial polished (but not pressed) plate. Both the 60-inch and 100-inch mirrors at Mt. Wilson Observatory are made of a kind of plate glass, and not "optical glass" as the term is generally understood.

At present the Bausch and Lomb Optical Co. is apparently the only commercial institution in this country making optical glass which can be used in constructing optical instruments.

Glass: Enthusiasts who become deeply interested in glass working will pick up more or less valuable information from *The Glass Industry*, a monthly technological journal published in New York.

Speaking of glass making, Hodkin and Consen's *Textbook of Glass Technology* is the last word. While it is primarily for the manufacturer, no one who is seriously interested in optics will fail to profit by a knowledge of glass manufacture. Professor W. E. S. Turner's *Constitution of Glass* is rather advanced.

The Journal of the Society of Glass Technology, published quarterly by the Society of Glass Technology, Sheffield, England, occasionally contains material

of interest to advanced amateurs. It is intended primarily for glass manufacturers. A few large libraries keep this journal on tap.

Wassell and Blacklock Letters: Lest they be lost sight of, mention is made of the long series of letters on mirror making published many years ago in *English Mechanics*. Ellison (page 74) refers to those of Wassell, though they continued until 1886, not merely until 1883, as stated by him. The dates follow: For 1881: Sept. 23; Nov. 11; Dec. 9; Dec. 30. For 1882: Jan. 13; Mar. 24; Apr. 14; May 12; June 16; Aug. 11. For 1883: Mar. 30; Apr. 27; May 4;

A HOME MADE TELESCOPE

Made by E. L. Worbois and described in the Scientific American, May, 1928, page 448. The sights are like enlarged peep-sights on a rifle. This is almost as satisfactory as a finder.

June 1; June 8; July 27; Aug. 31; Nov. 9. For 1884: Feb. 8; May 30; June 6; July 4; Aug. 22; Oct. 24; Dec. 12. For 1885: Feb. 6; Apr. 3; May 29; Nov. 20. For 1886: Feb. 5; Mar. 26; June 4; Sept. 17; Nov. 12. A second series, by Dr. Blacklock, may be found in the volume for 1895, pages 403, 449, 495, 543; and in the volume for 1896, page 26. Much of this matter is out of date, but the dyed-in-the-wool enthusiast who enjoys sherlocking around public libraries

and poring over ancient, dusty tomes in search of hints will enjoy hunting up this series. (Purchasing the back numbers would be a most difficult task. A few large libraries contain them; for example, the Library of the Associated Engineering Societies, 13th Floor, 25 West 39th Street, New York City.) The advanced amateur should not look upon the methods of the old-timers as necessarily sacred, nor consider in the light of a sacrilege a wide deviation from them. This, in fact, is the way progress is attained, for a few such wild stabs in the dark, out of a multitude attempted, will likely land on something new and wholly worth while. One great trouble with mirror making in the past has been that there always has been an "established way", to deviate from which constituted a desecration of a holy of holies. "Try anything once" has proved

A HOME MADE TELESCOPE

Made by E. L. Worbois and shown on preceding page. Folded up for transportation in a car. The mirror is an 8 inch.

a fruitful source of discovery in all fields of science. With several thousand workers doing that, there is no telling what may be hit upon.

Estimating Fineness of Grinding: Dr. James Wier French rates carbo. at four or five times the cutting power of a corresponding grade of emery (*Transactions of the Optical Society,* Jan.-Feb., 1917). It will do no harm to try emery for a stage or two of grinding, just to see what the old-timers were up against before the days of faster abrasives. (The Editor tried it and came away with a profound respect for their patience.) Other notes follow, chosen from Dr. French's article. In working with carbo., emery or sand the abrasive effect, determined by weighing the quantity of glass removed, was found to be directly proportional to the load applied, and is directly proportional to the

speed. Dr. French made interesting quantitative determinations on fine ground surfaces, refining the method described on page 279—"How can I tell?" . . . . etc. He placed his glass on edge upon a table graduated in degrees around its periphery. Near it he placed an electric lamp, permanently fixed. He then placed his eye so as to catch the image of the filament in the glass. "If the plate (*i.e.*, the glass) is rotated," he says, "so as to reduce the angle of incidence, the eye being moved so as to keep the image central, there will be observed at one point an abrupt change in the whiteness of the image, due probably to the scattering of the more intense short wave rays.

"In the first instance some difficulty may be experienced in observing the change, but once it has been observed, no difficulty should be experienced in locating the point of change to within half a degree without the use of any special apparatus other than the graduated circle.

"If now the angle of incidence is still further reduced, the image will quickly become red and then rapidly fade away. The point of maximum redness can be recorded to within three-quarters degree . . . . These two points—where the white image changes and the red is a maximum—afford a definite record of the surface that is independent of the personal element or the intensity of the illumination. Repeated measurements, accurate to within half a degree, can be made of the point at which the image disappears, but as these measurements are not independent of the illumination and the individual, it is necessary to standardize these factors for closely accurate work."

Dr. French determined microscopically that the particles removed in pitch and rouge polishing are about 1/25,000 inch in diameter.

Hardening Brass: The little brass ears at 1, on the prism tube C, on page 29, may be made springy simply by tapping them with a hammer. This hardens brass. To soften brass, heat it in a flame.

Paint for Inside of Tube: A dull or flat black paint is best for the inside of the tube. Ordinary black house paint well doped with boiled oil will do fairly well. Better than anything is "coach black", which comes in cans and is to be diluted with turps, for use. This gives the dull black which one sees on the inside of cameras and other optical instruments.

An Adapter Tube for eyepieces is often a decided convenience, as the length of the eyepiece may not always permit handy focusing. The adapter is a piece of tubing 3 or 4 inches long, into which the eyepiece fits, and which in turn slides within a larger tube—usually the one that holds the prism on its opposite end. Brass tubing that fits other tubing, inside and out, may be purchased from Patterson Brothers or Chas. H. Besley and Co., but one should specify that it must telescope smoothly.

Three in One: If one finds that one enjoys the first job of mirror making, the chances are that one may make several mirrors and learn the art. A good idea, therefore, is to provide for two or three sizes, when making the mounting. For example, in the simple mounting shown on page 29, the board in which the mirror rests can be recessed for 6-, 7- and 8-inch mirrors, each recess being turned out in the bottom of the next larger one. The size of prism should be calculated for the largest mirror.

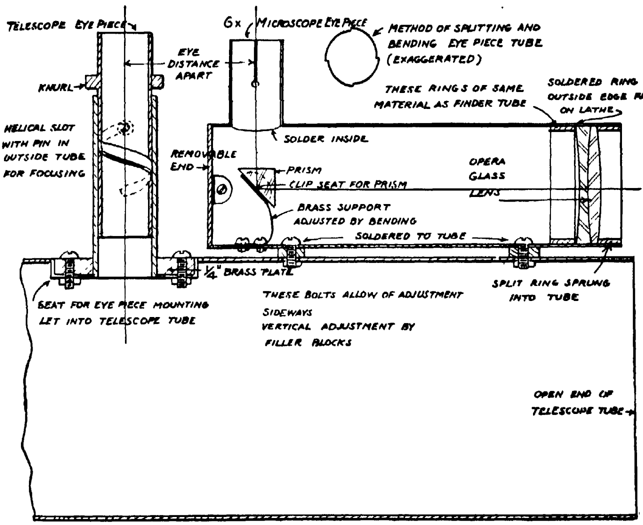
Making a Flat: Some prefer to make their own diagonals and silver them, rather than use a prism; others wish to use a flat for testing at the focus (page 16); another use for a flat is described on page 36; finally, the advanced amateur is likely to make a flat just to find out whether or not he can make a passable one. On page 57 he will find how to go about the task. Of general interest and possible application is the matter of making master flats for testing the precision of machine tools. In all mechanical inventions involving precision work master flats are the final court of reference for the accuracy of gages, micrometers and other measuring instruments. Scientific Paper 436 of the Bureau of Standards (Washington, D. C.) entitled *Interference Methods of Standardizing and Testing Precision Gage Blocks*" (the familiar Johannsen blocks or "Johnny blocks"), by Peters and Boyd, explains thoroughly how these master flats are employed. The following is an abstract of the paper, which may be purchased only from the Superintendent of Documents, Government Printing Office, Washington, D. C.; price 10 cents (do not send postage stamps). From it one will pick up some valuable knowledge, whether he plans to make a flat or not.

"Precision gages, which are blocks of metal (usually steel), having two opposite faces plane, parallel, and a specified distance apart, are used in the shop as reference end standards for checking micrometers and other measuring instruments, and also as distance pieces or size blocks for precise mechanical work. The extensive use of precision gages necessitated by the small tolerances allowed in the manufacture of interchangeable machine parts has required more accurately determined end standards and more rapid and precise methods for comparing gages with these standards than have been previously available. Since comparisons of end standards with line standards by means of micrometer-microscopes and of precision gages with end standards by means of contact instruments are subject to appreciable errors, methods which make use of the interference of light waves were used in making these measurements. With the interference methods described in this article the planeness and parallelism errors of precision surfaces can be measured, and the length of standards gages can be determined by direct comparison with the standard light waves with an uncertainty of not more than a few millionths of an inch. The errors of other gages can be determined by comparison with these calibrated standards with equal precision. This process makes the standard light waves, which have been determined to one part in four or five million relative to the international meter, the standards of length for this work. The apparatus used for calibrating standards and comparing other gages with these standards is illustrated by line drawings and thoroughly explained."

On this subject, see also *American Machinist*, Sept. 1, 1921, pages 329 to 331, by Porter, who has made a number of master flats for various industries. The publisher's supply of back copies is sold out, but copies can be obtained from the H. W. Wilson Company. Most large public libraries also contain the files. Those who have failed to obtain copies of various technical and scientific articles mentioned can, on a pinch, and if the incentive be strong enough, have photostat copies made by some of the larger public libraries, on payment of a fee which will bring the cost of the average article to not over two or three

dollars. The New York Public Library, Fifth Avenue, New York, handles this work by mail, and issues application blanks and a scale of rates. You name the book or article; they do the rest.

Finders: For a finder one may rig up some kind of a gunsight, perhaps employing radium paint, visible at night (The Radium Luminous Material Corp.). In any case, a finder is a decided convenience. One which was purchased from the Gaertner Scientific Corporation for a moderate price proved applicable to almost any telescope and well worth the price paid. A good



Drawing by R. W. Porter

DETAIL OF THE ROGERS HOME-MADE FINDER

one will include a field of view at least 3 degrees (six moons) in diameter. H. L. Rogers, a real estate broker, made his own finder and equipped it with a small total reflection prism. By placing the finder near the eyepiece he was able to use both eyes at the same time in locating a star, an ingenious wrinkle. The Editor asked Mr. Rogers to describe his finder, which he has done as follows: "I took one lens of an old pair of opera glasses of about 1¾-inch aperture, and bought at a hardware store a tube to fit. The lens was seated against a piece of the same tube, split, shortened, faced on the lens side, sprung inside the tube and soldered in. There is an outside retaining ring also, made like the other. Before deciding on the length of the tube the focal length of

the lens must be ascertained (by focusing in the parallel sun's rays, not those of a local light source, and then measuring distance from lens to clearest obtainable image—Ed.). The eyepiece holder for the eyepiece is soldered to the main tube from the inside. Two lengthwise hacksaw cuts divide the eyepiece holder into four prongs which may be sprung inwards to hold the eyepiece. The latter was a low-powered microscope eyepiece smaller in diameter than the 1¼-inch American standard. The sketch shows the prism which is held in a sheet brass clip soldered to a support of stout soft brass. This may be adjusted by the screws and by bending. The end fixture for the main tube is merely a piece of sheet brass with a ½-inch strip soldered across the inside face, and bent at right angles to take a small screw at either end through the main tube. Finally, the finder was attached to the telescope tube at a point so that I could use both eyes at one time in finding an object, a convenience whose unusual value will instantly become apparent on using it. The finder must, of course, be adjusted so that its field of view coincides with that of the telescope. No cross-hairs were used, as it is easy to place the star in the center of the field of the finder, or sufficiently near the center to bring its image somewhere on the main mirror."

To this Porter adds: "It would, however, be easy to add cross-hairs, or at least a kind of sight, simply by bending a piece of spring brass wire into suitable form. If the eyepiece used on the finder is positive, the sight will be snapped inside the tube just beyond the field lens; if a negative eyepiece is used, remove the field lens and place the sight between the two lenses of the eyepiece, against the diaphragm, where it will be in sharp focus. The idea in either case is to place the sight in the focal plane of the eyepiece used."

In one of his little brochures or "hobbygraphs" John M. Pierce tells how to make the objective lens for a finder; in another how to make the eyepiece.

Cemented, Built-Up Disks: It is possible, by cementing together two relatively thin disks of glass, either with or without spacers between them, to build up rigid disks of the desired thickness-to-diameter ratio, but will they stay rigid? Evidently yes—for a time: weeks, months, perhaps longer. Alan R. Kirkham, also others, after numerous experiments at first very promising, later disappointing, comments as follows. "There are plenty of cements which would be tough enough, hard and permanent enough, but they have all failed, not because of inherent deficiency in the cement, or any lack of adhesive qualities, but rather because of the difference in thermal expansion of the cement and the glass. A conceivable explanation is that, when the temperature changes, the glass may try to expand faster than the cement, or vice versa, with the result that stresses, perhaps of several tons, are set up within the disk, and the constant small changes of temperature eventually force the cement free from the glass, and these disks come apart within a few months. Many have tried soft cements, like pitches and balsams, but it is fairly evident that several disks piled up, as is often done, will deform as much or more than a single disk would, unless they are rigidly fastened together and remain so." Some day, however, this problem may be solved.

How Plate Glass Is Made: Polished plate glass and pressed plate glass

are apt to differ in qualities required by the telescope maker. Pressed plate is forced under pressure into a mold and is usually permitted to cool too rapidly to permit good annealing and freedom from internal strains. It can be told by its rough appearance. It is also less expensive—a poor economy, however, for the telescope maker. Polished plate is not necessarily well annealed, at least it is not *necessary* to polish it in order to anneal it; but plate that is worth the cost of polishing actually is always annealed. This is done by slowly moving it through a tunnel 800 feet long called a "lehr," whose temperature decreases from one end to the other. This passage requires five hours. A visit to a plate glass factory would be of interest to the telescope maker, to see how the manufacturer goes at the job of accomplishing on a mass production scale the task which we amateurs do on a small scale and at such cost in physical effort. The molten glass at 2,500 to 3,000°F is poured upon a large steel casting table, a steel roller spreads it out just as a cook rolls out dough, and it quickly drops to a red heat. Then it is annealed in the lehr. Next it is placed on rotating tables and ground by big disks under heavy pressure, with sand and water. Finer and finer sands are followed by several sizes of emery. The polishing is done by means of a battery of 18-inch buffing disks of felt, using rouge. These buffing disks steam under the heat generated by friction. In all, about an eighth of an inch is removed from either side of the glass during these operations. The grinding of a sheet about 25 feet in diameter requires 500 horsepower. From this it ought to be easy to figure out the boiler horsepower of an amateur telescope maker.

Learning to Understand the Knife-Edge Test: It requires years to learn all about the knife-edge test—although enough can be learned about it on a single occasion to use it. There is almost no end to the fresh insights about shadows, their significance and fine interpretation, which more and more use and general familiarity with them, on more and more mirrors, will keep right on giving.

In explaining things that are not at first easy to grasp, the exact turn of a phrase, like that of an ankle, has everything to do with its power to reveal niceties, and therefore the mirror makers who are closer to their maiden efforts often describe the test (not the ankle) more graspably, and with a fresher point of view, than the old-timer. For example, Robert Hurley's comments, written when their author was a student at the University of Cincinnati, are to the point: "If the pencil of rays," he says, "be cut with the knife-edge at the point where they focus, until half of the image has been observed, the light that passes the knife-edge will have come in equal amounts from all parts of the mirror, provided the mirror is a perfect sphere. When the observer places his eye so that it catches the light that passes the edge, he will see an evenly lighted disk. Suppose there is a mound in the center of the mirror, that is slightly elevated from the surface that would be a perfect sphere. The light coming from one slope would be thrown more into the obscured side of the image, while that from the other would be thrown into the free side. The observer would then see an exaggerated light and shadow relief of the errors on the surface." (This is very clearly stated.) He continues: "The paraboloid can be divided up into a number of annular

zones, each of which has a definite radius of curvature. If the radius of curvature of the central zone be designated as R, then the radius of any zone will be R + r^2/R, where r is the radius of the zone." We do not recall anyone previously explaining r^2/R in just this way, the usual way being to state that the difference between foci of inner and outer zones is r^2/R. While this is the same thing, the way quoted above seems to be a clearer statement for the beginner. "Besides this," Hurley continues, "the paraboloid can be recognized by its characteristic pie-shaped appearance when tested at a radius intermediate between that of its center and outermost zone." A paraboloidal mirror is usually tested, not at its "center of curvature," as is commonly stated in print, for it has no such thing, but at its mean center of curvature (c of c).

Another amateur who has a flair for stating things graspably, is Hugh Hazelrigg of Evansville, Indiana. In a letter he explains the behavior of the characteristic paraboloidal shadows at mean c of c, thus: "Keep in mind that when the knife-edge cuts into the rays reflected from a spherical mirror from inside the center of curvature, the shadow moves in the same direction as the knife-edge, but when the knife-edge cuts into the rays outside the center of curvature, the shadow moves in a direction opposite to that of the knife-edge. Now the outer part of a paraboloidal mirror has a longer radius of curvature than the inner part. Consequently when we place the knife-edge between the center of curvature of the inner part, and inside the center of curvature of the outer part, the shadow will move, in the outer part, in the same direction as the knife-edge and in the inner part in the opposite direction." We might look at the same thing as if we had two separate mirrors of slightly different focal lengths, one inside of the other.

Avoiding fatigue in the knife-edge test: Beginners often complain of eye strain from this test, but nerve strain—tension—is the usual cause of the headaches. When you learn how, you will be able to test for hours without any fatigue at all. First, arrange the set-up for the test so that your whole body is relaxed and sprawled out limp; have the knife-edge at such a height that the rays come into the eye just where it is when you are so deposited—no scrooching or stretching. Do not squint the eye or tense any facial muscle but compose your face blankly and then convey it that way to the knife-edge, looking as easily and naturally as if taking in the scenery on the other side of a keyhole. Do not close, half close or even squint the other eye; this is most fatiguing. Learn to ignore it, as all astronomers and microscopists do when looking through eyepieces. Finally, don't use up nervous energy over self-accusation because you cannot interpret the shadows right off. It takes a long while for this to become automatic. Probably no one reaches that stage very soon. Have faith, however, that it will come in time, and that fatigue will disappear.

Metal Template: "It is very difficult," J. V. McAdam of Hastings-on-Hudson writes, "for even a good mechanic to scribe a curve and file a *square* edge to within half a frog hair of the line. My method is to file a piece of thin brass to the approximate curvature, put a hole in either end and screw it down to the end of a rough T-square or board. Drive a nail through the other end at desired radius and into the work bench or a mahogany table.

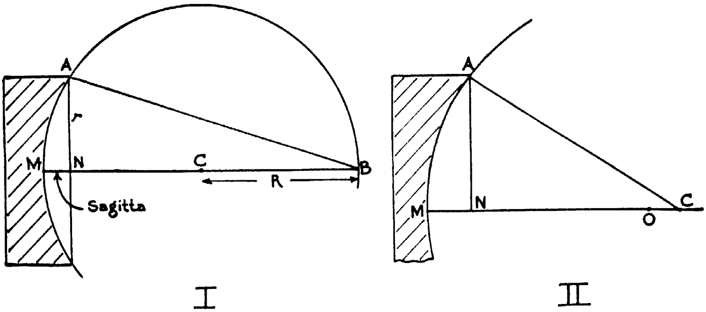
Clamp a file to the bench so that the edge contacts the brass and push the T back and forth over the file, gradually rapping the file into closer contact as it cuts away the high spots, the last few strokes having very light contact." McAdam didn't think we would actually put that in—about the mahogany table and the hairy frogs on the romantic Hudson. Never trust an editor.

Littrow Type of Objective: Ordinarily the rear surface of the flint component of an objective lens is altered to obtain color correction, but by selecting the proper glasses (right dispersion) the rear surface may be left flat, and this lens is fairly good—not, of course, first-grade but fair to middling, depending on what the criterion is. A good finder may be made this way, likewise a good terrestrial refractor, or a fairish astronomical refractor. This type, in which the crown component is equi-convex and the fourth surface flat, is known as the Littrow type of objective and is an old one. Donald E. Sharp of Bailey and Sharp, Hamburg, N. Y., gives the following simple rule for computing the radii, which is reproduced from his circular by permission: "Make each of the first three radii numerically equal to four-tenths the desired focal length. The last radius is found by multiplying the first radius by the flint dispersion, and dividing the product by the difference between the flint dispersion and twice the crown dispersion. If the flint dispersion is greater than twice the crown dispersion the last radius is convex; if it is less, then the last radius is concave. The crown is in front and is equi-convex. The flint is concave to fit the crown on one side and may be cemented if desired. Quite commonly the last surface of the flint has such a long radius that it may be finished flat. Example: Flint has dispersion 0.01670; crown has dispersion 0.00800; desired focal length 64 inches. Crown, first radius, $0.4 \times 64 = +25.6''$ (convex); crown, second radius, $0.4 \times 64 = +25.6''$ (convex); flint, third radius, $0.4 \times 64 = -25.6''$ (concave); flint, fourth radius, $[25.6'' \times 0.0167] \div [0.0167 - 2\ (0.008)] = +611''$ (convex). When the flint dispersion is twice the crown dispersion, or very nearly so, the last surface of the flint is plane, and the objective consists of a double convex lens and a plano-concave flint. The first three curved surfaces are of equal radius in any case. The ratio of diameter to focal length is usually not over 1 to 15."

Scratches from rouge: A large part of the rouge on the market is so inferior in quality that experienced amateurs are following Ellison's advice (page 88) and washing their rouge before using it. There are various ways. S. H. Sheib writes: "I lay down two pieces of cotton flannel, each 8 inches square, fluffy side up, and on this put about 4 ounces of moist (paste) rouge, tie it up in bag shape and work it under water, à-la-Ellison. Another way is to stir up 4 ounces of rouge in 3 pints of water, allow it to settle 1 minute, then carefully pour the liquid part into a two quart jar. Next let this settle five minutes and pour off the liquid, using the residue at the bottom." This last liquid may also be saved and its content of very fine rouge, after a few days' settling, used as finishing rouge. Some workers do coarse polishing with American Optical Co. rouge, and finish with Bausch and Lomb's best. Harold Lower is partial to black "rouge," which he finds very free from scratchiness.

Sagitta twice r^2/R: To find the sagitta of a spherical mirror, given r = radius of mirror and R equals radius of curvature: In the figure I, MAB is a right angle, being inscribed in a semi-circle. MN over r equals r over 2R —MN (since the normal to the hypothenuse from the right angle is the mean proportional between segments). But when the sagitta is relatively small, as in a speculum, MN equals $r^2/2R$.

Another demonstration given by Pierce is as follows: To find the distance between centers of curvature of middle and edge zones of a paraboloid: Draw normals, as in II, from A and M. Then C is the center for zone A, and NC is the subnormal for the edge zone. O is the center for the central zone and MO is the subnormal for the same zone. MO equals NC (since all subnormals of a paraboloid are equal); therefore, OC equals MN. In a speculum, MN approximates the sagitta, and the centers shift an amount equal to the sagitta itself, or $r^2/2R$. If the knife-edge and lamp move together, the shift



DEMONSTRATIONS BY JOHN M. PIERCE

equals OC, these points being the centers of curvature of the edge and middle zones, or $r^2/2R$. But if the knife-edge alone is moved, the shift will be twice that amount, or r^2/R. (Q. E. D.)

Fused Quartz or fused silica is the ideal substance for a telescope mirror, principally because its coefficient of expansion is so very low—only 1/18 that of plate glass—that mirrors made of it can be figured and used under all temperature changes without detriment to the curves. This material was extremely costly until 1924 when the General Electric Company announced that a way to make disks up to 10 inches in diameter had been developed at the Thomson Research Laboratory in Lynn, Mass. Prof. Elihu Thomson, Director of the Laboratory, has been an amateur telescope maker for the past 60 years and he has forwarded the research on fused quartz or silica from that point of vantage. The following statement was prepared by Dr. Thomson:

"For twenty-five years I have borne in mind the great desirability of procuring fused silica disks of glass for astronomical mirrors. It is its low

coefficient of expansion and its consequences which confer such great superiority as the silica disk possesses. This may be stated under several heads.

"1. Disks require but little annealing, while with the large glass this is a matter of great difficulty. 2. They can be rough ground by a carborundum wheel without danger of fracture, an operation difficult with glass and rarely resorted to. 3. The disks can be made very thick and rigid more easily than with glass. 4. The fine grinding (or smoothing before polishing) is carried on with great facility, and the surface before polishing is usually of finer grain than with glass. The fused silica is considerably harder than glass, and not so easily scratched. 5. The polishing proceeds readily and can be carried on regardless of temperature changes. Incidentally, there is less liability of scratches forming in polishing. 6. In very accurate work, figured by polishing, as in high grade surfaces of astronomical mirrors, the polishing and testing need not be interrupted as with glass by long rest periods, with the mirror disk kept jacketed in felt for equalization of temperature. (For the benefit of beginners: only large mirrors are here referred to.—Ed.) This is very important and involves great saving of time. 7. In service, none of the precautions against temperature variations and distortions arising therefrom are needed, and even in solar work with full sunshine on the mirrors, no evil result follows.

When it is remembered that it took two years of testing and polishing for figure, involving long interruptions for equalization of temperature, to produce the 100-inch glass mirror mounted at Mt. Wilson, near Pasadena, California, the advantage offered by fused silica is evident.

"The optician will welcome the possibility of obtaining so-called flats of desired sizes, not subject to temperature distortion," continues Dr. Thomson, "while the making of accurate flat surfaces is evidently greatly facilitated. The silvering of surfaces of fused silica appears to be no more difficult than with glass, with the advantage, however, that the former can be warmed without risk when such warming is needed to assist the formation of the silver deposit."

The manufacture of fused quartz was described in the *General Electric Review* (Schenectady, N. Y.) June, 1924. Disks of from 6 to 10 inches diameter may be obtained, but the present cost of manufacture on a small scale still puts them in the luxury class. Porter figured the first disk after the new process of manufacture was developed and found the figure entirely indifferent to temperature change, whether the disk was worked in sunlight or dipped into hot water and immediately given the knife-edge test. Quartz disks are now being used for various purposes at observatories and in physical laboratories. To take advantage of the non-expansibility of quartz the amateur should, however, be able to work within a fairly close limit of precision. It would be no use, for illustration, to employ quartz for avoiding changes in figure which were already masked by larger errors in the figure.

As fused quartz is expensive, can a tool of plate be substituted? Regarding this The Editor inquired of E. W. St. Clair, Director of the Standardizing Laboratory of the General Electric Company at West Lynn, Mass., himself an amateur telescope maker, who wrote as follows:

"I have delayed answering your letter of February 23rd until I could talk with Professor Thomson himself, as my experience with quartz has been with cast iron laps rather than with glass laps. I discussed this question fairly thoroughly with Professor Thomson who feels from personal experience that there is no difficulty at all in using glass for the tool when working quartz. The Professor points out that it would be necessary to be reasonably careful about the temperature of the glass tool during the final grinding stages.

"I have found from working several pieces of quartz, including one astronomical mirror, that cast iron makes a very good lap material but, as is of course well known, one must be very much more careful about scratching during the fine grinding stages than is necessary when one is using the glass tool.

"Professor Thomson also points out that it might be possible in furnishing quartz disks to furnish two disks. The one to be used as a tool need not be of the same high quality as the one intended for the mirror.

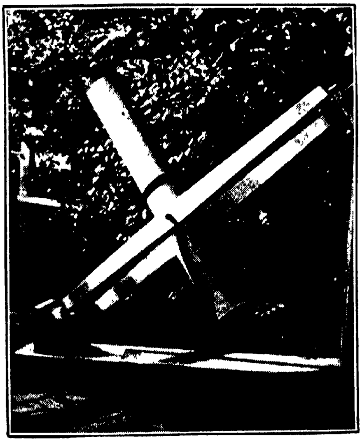
"Based on a great deal of experience in the grinding and polishing of still harder materials than quartz (gem minerals for scientific instruments, etc.—Ed.) I doubt if there would be any great difficulty in grinding and polishing quartz, using most any type of reasonably hard material. During the final grinding stages I think it is only necessary that the material be of such a nature as not to charge with the abrasive compound unless a material so soft as to be almost a polishing lap be used, in which case the charging is not serious inasmuch as the grains will all come to one level very quickly."

John C. Lee writes as follows: "My quartz mirror was ground on a lead lap. The lap was fashioned on a lathe to the desired curvature and then grooved so that it looked like a conventional pitch lap (see page 149). The surface of the lap seemed to wear away very slightly as the grinding proceeded, and only enough to improve it."

Pyrex: Next to quartz in low expansion and contraction qualities comes Pyrex, having about 6 times the linear expansion of quartz but still only one-third that of plate and optical glass. This explains why the familiar Pyrex baking ware does not break when suddenly cooled on the surface; common glass contracts so rapidly on the outside surface when chilled that the stresses set up are too great for it and it fractures. Pyrex is a borosilicate glass containing borax or boric acid or both, and is manufactured by the Corning Glass Works. Whether the beginner should choose this kind of glass, or plate glass, which has three times the expansion coefficient of Pyrex but is not so hard, and is therefore easier to grind and polish—requiring approximately half as much time—is perhaps a toss-up. The unanswerable question is, can the novice figure his first mirror accurately enough so that the gain in stability afforded by the low-expansion characteristics of Pyrex disks will be exploited? If on his first job he cannot do this, the advantage will be illusory. Anyway, his demands on a mirror's excellence, and his skill, are not likely to be as high as they will be later on, after he has made two or three mirrors. On the other hand, the Pyrex disk is neater—perfectly round because formed in a turned mold, while plate disks are likely to vary a sixteenth inch or so from round. This does no harm but is not quite so pleasing, esthetically. The

hardness of Pyrex requires no added skill. A harder lap—less likely to cause turned edge—may be used without scratching. Best of all is comparative freedom from temperature effects in figuring.

Glass Mirror Substitutes: Although the beginner will wisely choose plate glass, and the average amateur will stick to it, there are a number of other materials which may be regarded as possible substitutes. Some still require more research, some are a demonstrated "wash-out" and others, like quartz, are a grand success but are not at present as available as one could wish.



A HOME MADE TELESCOPE

Made by Earl O. Graff and described in the Scientific American, September, 1927, page 281. This type is described in Part I, Chapter 2; see especially Figure 25. A. W. Everest made a mounting of the same double-forked type and devised a simple braking or holding device which proved ideal. A discarded baby carriage wheel with rubber tire removed was applied to either axis. In the groove of these wheels the brakes, consisting simply of strips of wood, one on either side of each wheel, and held lightly against the wheels by means of spiral springs, were allowed to run. This held the tube whereever placed, yet permitted easy motion.

Since many of the advanced amateurs will ultimately be likely to consider trying these substitutes and may have difficulty obtaining authentic information concerning them, they are described below. These descriptions are purposely inserted in some cases in order to call attention to the drawbacks of certain of them. This may possibly forestall futile efforts. Nevertheless, the resource-

ful amateur who loves to explore the byways is as likely as anyone to hit on some invaluable discovery, hence the consideration of the various materials is encouraged. Dr. F. G. Pease of Mt. Wilson Observatory, in canvasing possible substitutes for glass for very large reflecting telescopes, makes the following statements (in *Publications of the Astronomical Society of the Pacific*, August, 1926):

"Another method early proposed was to quarry a block of obsidian and fashion it into a mirror. Obsidian is a volcanic product occurring in large masses, usually fractured into small pieces; but Dr. F. E. Wright of the Geophysical Laboratory informs me there is a ridge in Iceland, from which blocks could be cut far larger than would be required for a 25-foot disk. Obsidian is easily ground and polished, and silvers well. It contains, however, quantities of fibrous and crystalline material which cause defects in the polished surface.

"It has been proposed to build mirrors of concrete or cement and face them with silver. It is almost certain that such mirrors would be failures for the class of instrument which we are discussing. Concrete changes its form as it ages and no amount of grinding can remove its surface grain. With a coating of silver thick enough to cover this grain and permit a uniform surface, the differential expansion of the silver and the concrete would cause large distortions of figure, and the chances are the silver would buckle or peel.

"Various marbles, resins, waxes and grainless cements have been tried as mirrors, but fault can be found with all of them when considered from the standpoint of a large, permanent, precision mirror.

"Attempts have been made to coat various materials with alloys or metals by spraying with an air gun. Microscopic examination shows that such surfaces are grained and fibrous, and unfitted for fine astronomical purposes.

"There is a promising field for research in the investigation of metal alloys suitable for mirrors. When one considers the enormous number of possible combinations of metals, he has hopes of finding an alloy which would be light in weight, which could be cast either solid or as a ribbed plate, and which could be easily silvered, if not in itself possessing excellent permanent reflecting properties.

"Alloys are known which possess some of these desirable properties, and it may be that the addition of other metals, or new combinations of them, would yield the desired material.

"Metals very quickly adjust themselves to variations in temperature, and, consequently, would have a good figure most of the time. Their coefficient of expansion is large, but this property is not inherent in all alloys.

"INVAR, for example, is an alloy of 64 per cent steel and 36 per cent nickel, which has a coefficient of expansion practically equal to zero. Its reflecting power is not high, but it can be silvered. If it were possible to cast a large ribbed plate of *Invar*, or to build up a mirror from sheets and separators, it might serve our purpose.

"SPECULUM METAL is a bronze composed of 68 parts of copper and 32 parts of tin. Most of the early reflectors, including the 6-foot mirror of Lord Rosse,

were made of this material. Its reflecting power gradually drops from 70 per cent in the red to 50 per cent in the violet. It tarnishes in the open air and must be repolished and figured in the optical shop.

"STELLITE has been used for mirrors in small sizes. Its reflecting power varies from 64 per cent at 6500 to 54 per cent at 4000. (6500 refers to wave-length in Angstrom units and would be in the red; 4000 would be in the violet.—Ed.)

"MAGNALIUM mirrors made of 31 parts of magnesium and 69 parts of aluminum, possess a reflecting power of about 83 per cent in the visual region, which gradually drops to 67 per cent at 2510 (in the ultra-violet.—Ed.). Early mirrors made of this material were poor, but the art of casting aluminum alloys has since improved greatly and it is possible that good light castings could be made today.

"STAINLESS STEEL MIRRORS containing 11 to 14 per cent chromium, now enjoy considerable use in small sizes and possess the advantage of retaining their brightness over long periods of time under circumstances which would ruin a silver coating. Measurements of their reflecting power yield values from 60 to 80 per cent in the visual region of the spectrum. The coefficient of expansion is higher than that of steel.

"The alloy which the astronomer looks forward to might be called 'Mirror-ite,' and the time may arrive when metallurgists, by careful research, will so combine metals as to produce this remarkable material, having the reflecting power of silver, the zero coefficient of expansion of *Invar,* the freedom from tarnishing of stainless steel, and the lightness of magnalium.

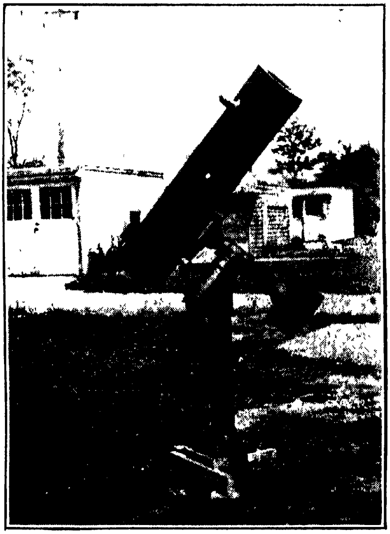
"Telescopes have been proposed in which many independent paraboloidal mirrors all point to the same spot. The mechanical mounting of such a system of mirrors would not be difficult to build. The light-gathering power of such a telescope would equal the sum of that gathered by the individual mirrors, but the resolving power would be only that of a single mirror. Owing to the fact that most of the mirrors would be used in oblique positions, the quality of the image would be poor.

"The construction of a large mirror composed of separate pieces, whose surfaces are parts of a single paraboloid would be more difficult to make than a single disk. To grind and polish the parts simultaneously would require a large solid backing. To grind and polish each part individually would involve an enormous amount of 'local' work. The resolution of such a compound mir-ror would equal that of a single mirror of the same aperture, provided the pieces were in the shape of sectors whose adjoining edges were covered by the diaphragms supporting the secondary mirror. If many small pieces were used each image would be accompanied by surrounding spectra, just as though the mirror were covered with a grating."

OBSIDIAN or volcanic glass is usually black. The Editor purchased a chunk of this mineral, obtained originally in Utah, from Ward's Natural Science Establishment, and Porter sawed out of it a 2½-inch disk, ground it, polished it and figured it. He states that "it sliced as readily as glass. The only difference I could note between working obsidian and plate glass," he con-

tinues, "was that the obsidian would not take quite so fine ground a surface as that of glass, and a little longer time was correspondingly required in polishing. The resulting surface was a lustrous black, giving an admirable background for showing Newton's rings by ordinary daylight, when brought into contact with a glass flat." Obsidian in some cases is pure glass, in others a mixture of glass and crystals, depending on original rate of cooling from lava.

Invar, an alloy used for tapes, etc., because altered but little by temperature and having the smallest coefficient of expansion known, has been tried



A HOME MADE TELESCOPE

The mirror is a 6 inch. The mounting is built around heavy standard pipe fittings, yet they are none too rugged. Many telescopes are mounted too lightly and thus are anything but rigid. It is hard to overdo the matter of rigidness. This telescope was made by Sheldon K. Towson and was described in the Scientific American, August, 1928, page 172.

out by at least one amateur, G. H. Lutz. He has devoted years to research on various alloys regarded as mirror candidates, and has made seven mirrors of *Invar*. He states that, in common with all alloys that he has tried, it reveals its crystalline structure when polished, the crystals of the softer ingredients not behaving the same as the harder parts. *Invar* is a copyrighted name;

some refer to this alloy as "36 per cent nickel-steel" or "thermostatic nickel-steel." The alloy is made by the Crucible Steel Company of America; the Holcomb Steel Co.; and the Simonds Saw and Steel Co. The finished *Invar* mirror must be plated to prevent tarnish, and, says Lutz, "the plating has its own problems that call for a lot of patience. Chromium and many other materials have been made use of for plating, and the end is not yet. I am still experimenting."

Stellite was tried by Lutz on several mirrors, one of which, a 10½-inch, he showed to The Editor. He says it cost him many hours to master, as the outstanding quality of this alloy is its extreme hardness and resistance to abrasion (also corrosion). This is why it is used for high-speed machine tools, knives, oil well tools, dredge dipper cutting edges, etc. The relative resistance to abrasion of Haynes Stellite is 4 to 9 times that of steel. Lutz states that he used up 8 inches of brass tubing and 4 pounds of carbo. in drilling a 1¾-inch hole through his mirror, made of this remarkably hard alloy, and, he writes, "I will not wantonly advise anyone to start to make a mirror from *Stellite*, as I do not wish to make any enemies. However, if one has a machine, plenty of time and unlimited patience there is a chance." The alloy, which is said to be one of chromium, cobalt and tungsten, is not cheap. Lutz had trouble due to the crystals of tungsten remaining above the surface, but the later results were gratifying when he obtained a form of the *Stellite* in which the tungsten was reduced to the lowest possible limit. He did not have to pay any attention to temperature while working it, the figure not being thus affected; cold water could be run on the hot mirror (this is also true of *Invar*). Air temperature changes during observation did not alter the figure, as with glass. The coefficient of expansion is about half again that of glass, but heat is conducted very much more quickly through all metals, hence the point is largely academic. The manufacturer states that *Haynes Stellite* reflects from 83 per cent of the incident light in the red to 68 per cent in the violet.

Stainless steel mirrors are made by W. Ottway and Co., Ltd., London, but not in paraboloidal surfaces. Ernest Brookings, metallurgist, Jones and Lamson Machine Co., has made recent experiments with chrome steel for mirrors.

Copper, electrolytically deposited, reflects 48 per cent in the blue to 90 in the red; commercially pure copper, 32 and 83, respectively. *Gold,* electrolytically deposited, 29 and 92. *Silver,* 86 and 95 (when untarnished, of course). Figures given are from the *Smithsonian Physical Tables* and are for perpendicular incidence and reflexion.

Rotating, Mercury Mirror: Dr. R. W. Wood, Professor of Experimental Physics at Johns Hopkins University, attempted in 1908 to make an automatically paraboloidal mirror of variable focal length by the theoretically practicable method of rotating on a central, vertical axis a round, shallow pan of mercury. Under centrifugal action the mercury takes on the figure of a true paraboloid. Using a 20-inch pan, a rubber thread transmission and a magnetic clutch, Dr. Wood obtained interesting results, the focal length being varied with ease by changing the speed. Minute irregular disturbances injured the perfection of the mirror's surface, despite the velvety transmission or drive.

In the *Scientific American,* March 27, 1909, Prof. Wood stated that the mirror was set up on a massive concrete foundation at the bottom of an old well 15 feet deep. To afford approach and room for the driving motor a second well was dug 6 feet away and the bottoms interconnected. A building with a sky hatch was erected over the wells. On a vertical axis a round, flat-bottomed basin was centrally mounted, its bottom everywhere absolutely perpendicular to the axis (necessary to prevent ripples) and filled half an inch deep with mercury. Around it, but carried on a support not at any place in contact with it, was a collar on ball bearings, driven from a motor by a rubber thread belt, and this was coupled with the basin by rings of horseshoe magnets on each. At 12 r.p.m. the f.l. was 15 feet, but at 20 r.p.m. it was only 8 feet. "On the whole," Prof. Wood wrote, "the definition was found to be surprisingly good when one considers the difficulties." In the *Astrophysical Journal,* March, 1909, Prof. Wood stated that surface ripples were at first caused by jars from the driving mechanism, but the addition of the magnetic clutch eliminated these; by jars from the bearings, but these were eliminated; by imperfect leveling, which set up a wave which was eliminated through very accurately plumbing the axis by centering the image during rotation; and, finally, by variations in velocity, which was the worst source and was not eliminated before the experiments were put aside. Damping the ripples with glycerine gave much better definition, and 5-second double stars were separated—a fair beginning. Prof. Wood then wrote: "It may be necessary in the end to use a motor, the speed of which is controlled by a clock." Today such clocks are everywhere—the work awaits the worker.

In a private communication Prof. Wood, in 1928, stated that the same experiments were continued the next year, and that he "got it to work much better. I put a 20-inch flat over it," he continued, "and had excellent views of the moon. The final conclusion was that constant speed of drive would eliminate the slight tidal wave, which was all that remained. I did not even have a synchronous motor."

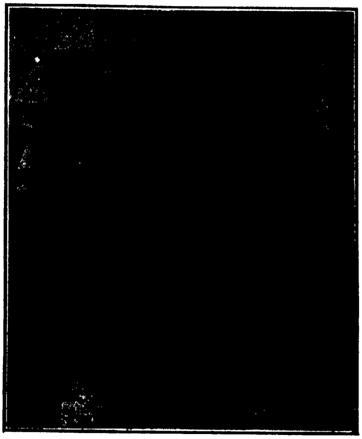
Prof. Wood also hoped to find some substance that could be fused, rotated and allowed to solidify when rotating, which would indeed be a quick way to make paraboloidal mirrors. To save mercury he also suggested using a copper vessel, only roughly paraboloidal. A thin film of mercury would climb up its slopes from the bottom when rotation began.

Cellular Mirror: Professor George Willis Ritchey, who figured the 60-inch and 100-inch mirrors at Mt. Wilson Observatory, and also the 24-inch reflector mirrors at Yerkes, has recently been working on a new cellular type of glass disks for optical mirrors of large telescopes. Each mirror disk of the new type consists of a front and a back circular glass plate, with a deep rib system also made of glass plates, between, and separating, the two. For mirrors from 60 inches in diameter up to the largest sizes ever considered the glass plates are all about one inch thick. They are made by the celebrated St. Gobain Glass Company, of a special, low-expansion glass perfected for this purpose. All plates for a given mirror are carefully selected for uniformity of thickness, of coefficient of expansion, and of flexure index.

The various plates are fitted together by fine grinding, and are then

cemented together with a thin layer of Bakelite cement much less than one micron [practically 1/25,000 inch.—Ed.] in thickness, thus forming a comparatively light and very rigid cellular structure. For a concave or a convex optical mirror the front glass plate is curved to the proper degree, but is of *uniform thickness* throughout, and is of the *same* thickness as all other plates composing the cellular disk.

In order to permit the air to circulate freely within the multi-partitioned interior round holes are cut through the sides of each rib or partition. A posi-



RITCHEY CELLULAR MIRROR

The whole structure, a 30 inch flat, is propped up on edge. The dark grid is the partition work of ribs and plates seen edgewise and through the thin mirror disk itself. The evenly spaced ventilating holes in the ribs may clearly be made out. Professor Ritchey states (Journal Royal Ast. Soc. Canada, July-August, 1928) that this mirror "has retained its optical figure for three years without change which can be detected by the most sensitive optical tests."

tive or forced circulation of air is used. Thus, adaptation to temperature changes takes place rapidly, especially as no glass thicker than an inch enters into the structure. The whole mirror has only one-fifth the weight of a solid disk, and holds its figure so perfectly under widely varied working conditions that no change of form can be detected with the most sensitive optical tests. For descriptions, see *L'Astronomie*, Feb., 1926; *L'Illustration*, April 24, 1926; *La Science et La Vie*, August, 1926; *Popular Astronomy*, May 27, 1927, p. 258.

Thus far Professor Ritchey has made mirrors of this kind (cellular) up to 60 inches in diameter which, he states, have remained optically plane under temperature changes such as those which occur in the open dome at night.

In a communication to The Editor, Professor Ritchey writes from *l'Observatoire de Paris,* where he is conducting many of his researches: "I am also developing two new types of photographic telescopes—the Schwarzschild and the Ritchey-Chrétien. The first of these has a large concave and a small concave (secondary) mirror; the second has a large concave and a small convex

RITCHEY CELLULAR MIRROR

The ribs and plates show plainly. This is Ritchey's second cellular experiment and is a concave mirror about 60 inches (1.50 meters) in diameter. Made in 1925-1926.

(secondary) mirror. Both have *new curves* of the mirror surfaces (other than paraboloid and hyperboloid). Both give much larger fields and much smaller, more concentrated, images of out-of-axis stars, than the paraboloid gives.

"The Ritchey-Chrétien type allows the shortest tube and smallest dome of any reflecting telescope type, about one-half those required for the type of the 60-inch and 100-inch at Mt. Wilson. The out-of-axis images are so small, round and concentrated that, on an average, for a field of 40 minutes of arc diameter, we will photograph out-of-axis stars which are at least two magni-

tudes fainter than those photographed with a Newtonian of equal aperture and focal ratio.

"This is a revolutionary result, and has been fully demonstrated in this laboratory. These small images demand refinements of guiding and focusing, of convenience and consequent efficiency of the observer, and of protection of the telescope mounting and tube from temperature changes and from flexure, *far beyond those attained at Mt. Wilson by the writer;* these refinements have all been fully worked out in this laboratory.

"The Schwarzschild type also gives a very large field of small, round images, together with very small focal ratio—as short as 2½ or 3 to 1—so that the light concentration for nebulae and faint stars is very great. But it is a most inconvenient type in use, unless it be used as a fixed telescope with a coelostat. When so used it becomes as important and revolutionary as the Ritchey-Chrétien. The two new tyes of mirror curves, used interchangeably, with various focal ratios, in conjunction with the fixed, universal telescope; together with the cellular, ventilated mirror disks made of extremely strong, rigid plates of low-expansion glass, will inaugurate a new epoch in telescope efficiency, in astronomical photography, and in accuracy of astronomical measurement."

These new conceptions are described in *L'Astronomie* in a series of six monthly articles beginning December, 1927; also in *Journal Royal Ast. Soc. Canada,* beginning with the May-June issue, 1928.

In the first article Professor Ritchey outlines his plans for a modern observatory with a great, vertical, fixed telescope having a coelostat and quickly interchangeable, cellular mirrors of the two new types, Schwarzschild and Ritchey-Chrétien.

Commenting on the first edition of *Amateur Telescope Making,* Professor Ritchey writes: "I am *most* heartily in sympathy with your efforts in regard to amateur optical work such as you describe in the little book which you so kindly sent me. Henry Draper's remark that 'the future hopes of astronomy lie in the multitude of observers, and in the concentration of action of many minds' is true. The greatest single need of astronomy today is the thorough popularization of it. This is easily possible by means of the finest attainable astronomical photographs. Astronomy could have, and soon *will have,* a thousand devoted friends assisting in every way in its development, where it now has one such friend."

The amateur should read well Ellison's comment on page 73. The professional, he points out, has nearly always started as an amateur. No professional has risen to higher attainments than Professor Ritchey.

Suction Mirror: Another unusual but possibly worth-while effort would be the conversion of a flat mirror into a paraboloid by atmospheric pressure. By producing a partial and variable vacuum behind the mirror the latter will be caused to sag inward and the curve should theoretically be a paraboloid. One worker is known to be experimenting with this method at present, while Porter states that he tried it out in a preliminary way in 1910, getting far enough with it to conclude that it was worth further effort.

Magnesium Oxychloride Mirror: This was described by F. Le Coultre in

Bulletin de la Société Astronomique de France, 1925, page 484; see also *Zeitscriften für Instrumentkunde,* 1926, page 588. The following is an abstract published in *Journal of the Society of Glass Technology.* "Several attempts were made to find a satisfactory substitute for glass for large telescope mirrors. The most successful results were obtained by mixing 100 parts of magnesium oxide with 24 parts of a one-half per cent aqueous solution of magnesium chloride which, on being thoroughly mixed, set readily into a hard, white mass. For the production of a concave mirror, the viscous mixture was poured into a mould, which was slowly rotated until the mixture became stiff. The

Science Service Photo.
PROFESSOR GEORGE WILLIS RITCHEY
From a photograph taken in his optical laboratory at the Paris Observatory, by James Stokley, 1927.

surface was then polished by means of emery and rouge. This mixture was not impervious to water, and it had the further disadvantage that it was attacked by CO_2, and the surface when silvered was not so good as a silvered glass surface. To overcome these defects the surface to be silvered was dipped into a 40 per cent solution of formalin. Afterwards the block was immersed, with its reflecting surface upwards, in a 2 per cent silver nitrate solution saturated with formalin, when the magnesium oxychloride immediately became covered with a brown deposit of silver oxide. The mirror was then taken from

the bath and dried. The surface became black through the decomposition of the protoxide into sesquoxide and metallic silver. When it was quite dry the mirror was polished with rouge. The finely divided sesquoxide was rubbed off and the metallic silver formed a layer on the surface, as hard and as highly reflecting as if on a glass surface."

While glass is still king, after many attempts to discover a better material, this does not prove that nothing better will ever be found. And amateur experimenters are as likely to make a valuable discovery as professionals.

Coefficients of Expansion and Relative Thermal Conductivities, both of which are likely to prove useful to the telescope maker, are quoted below, from the Smithsonian Physical Tables. These are for degrees Centigrade.

	Expansion	*Conductivity, Heat*
Plate glass	.00000891	
Crown glass	.00000954	.003
Flint glass	.00000788	.0018
Quartz, fused	.00000057	.0023
Speculum metal	.00001933	
Cast iron	.00001061	
Steel	.00001322	.107
Silver	.00001921	1.006
Stellite No. 6, cast	.0000165	
Stellite No. 6, forged	.0000146	
Invar	.000000374 to .00000044	(Bureau of Standards)
Stainless (chromium) iron	.0000010	(Bureau of Standards)

The decimal fractions quoted relate to that portion of the total dimension of the piece of material used, which the material will be increased or decreased by each increase or decrease, respectively, of 1 degree, Centigrade, in temperature. A degree Centigrade is equal to 1.8 of a degree, Fahrenheit.

Eyepieces: The principal types of eyepieces are the positive or Ramsden and the negative or Huyghenian. Both types contain an eye lens and a field lens, each of which is plano-convex. In the positive or Ramsden eyepiece these convexities both face each other; the focal plane lies just in front of the field lens; hence this type may be used as a low-power magnifying glass. In the negative or Huygens eyepiece the convexities face the same way—away from the eye; the focal plane of the negative lies between the lenses. Therefore it cannot be employed as a common magnifying glass. This is the easiest way to distinguish the two types.

Which type is the better? Reams of words have been written on both sides of this argument which never will be settled, because both types have their points. The positive has the larger field and less color, but dust on the field lens shows up prominently when the telescope is in use. The negative is the older type—much older, in fact.

Many prefer the positive, Hastings, three-lens type.

Then there is the so-called "erecting eyepiece" for terrestrial telescopes, to use when it is awkard to see things upside down. This consists of two plano-convex lenses with convex sides toward the eye, and still nearer the eye, two

bi-convex lenses. It erects the image, but its added lenses absorb and reflect a certain amount of light. A way to get around the lack of an erecting eyepiece is to face the object to be seen telescopically, get it into the field of view (inverted, of course), then turn one's back to it, thus inverting the eye itself so that the object is seen erect again.

A good diagram of an erecting eyepiece is shown in Todd's *New Astronomy.* Surveyors' transits are not equipped with erecting eyepieces, yet it is surprising to discover how soon one educates one's eye to see things well through them; even though seeing upside down. Numerous modern modifications of the basic types of eyepieces are described in Bell, *The Telescope.*

Old microscope eyepieces are suitable for use in a telescope, though they are usually the Huyghens type and give only a narrow field. If one will regard the eyepiece simply as a local magnifying glass for enlarging an image already formed by the mirror or objective lens of the telescope, just as if it were being used to magnify a tangible object, the real significance of the eyepiece of a telescope will be clear. This will also explain why eyepieces of different powers may be used with the same telescope.

A telescope is essentially (1) a big "eye" for gathering light (the human eye opening or pupil is also a light gatherer, but it is only one-third of an inch in diameter); (2) a properly curved instrument for bringing this light to a focus; and (3) a separate microscope for remagnifying it locally.

Grinding: The nature of the grinding operation is not generally believed to be the more obvious one. Without taking particular thought one might assume that the grains of abrasive act simply as plows, like the tool on a planer or shaper. It is thought, however, that this sort of thing occurs only when a grain drops into a depression in the one glass disk or the other and becomes lodged there. Mainly, the operation of grinding is something like what we would have on a large scale (visible) if we were to place a number of large steel balls on a cake of ice, with a second cake on top of the balls, and move the upper cake over the lower. Behind each ball, as it rolled, there would be a path, not planed or gouged out but *fragmented by pressure.* On glass we get something of the same thing with a glass cutter, which is not a cutter at all, but a local splinterer. With abrasives, the pressure directly under the particles is transferred downward and outward, and conchoidal chips of glass are pushed and sheared out laterally. And the greater the pressure the greater the depth of shearing involved. Grinding takes place in direct ratio to pressure per unit area, a point which answers the frequent query "How hard should I bear down?" The answer is: "Do you feel stronger than you feel patient, or more patient than you feel strong?"

Polishing, theory: "The process by which a ground or smoothed surface is turned into a polished one has been the matter of a good deal of debate," says F. W. Preston in *Glass Industry,* (Feb., 1928). "Some contend that the ground surface is liquefied by the drag of the polisher and, as it were, smeared about like butter on bread. Others contend that polishing is really just an exceedingly fine grinding operation."

Amateurs who are of a more or less investigative turn of mind and who

have access to a large city or university library will find in the files of the *Transactions of the Optical Society* (London) some interesting food for thought on this much-debated question. Exactly what actually takes place during the polishing operation? Is it simply a case of ordinary abrasion on a finer scale, or is it something else—perhaps molecular flow? Discussions of this question are to be found in several of the earlier numbers of the journal mentioned, most of which The Editor found to be available from the Optical Society. These journals came rather high, averaging about two dollars an issue, with a 25 per cent duty to pay the postmaster at this end. However, if one wishes to obtain them, inquiry should first be made direct to London, regarding the availability and price, postpaid, of each individual issue, for the prices are not uniform. Most readers will, however, be satisfied with a summary of these several theories of polish, which is quoted from a lecture by Dr. L. C. Martin of the Imperial College of Science and Technology and which was published in the *Journal of the Royal Society of Arts*, August 12 and 19, 1927, under the title "Recent Progress in Optics." The Editor has taken the liberty to insert in Dr. Martin's statement, within parentheses, the exact references to the *Transactions* wherever he mentions papers previously published in them.

"In 1907 G. J. Beilby described researches on the nature of the polishing process (*Transactions Opt. Soc.*, Volume 9, 1907, page 22); he distinguished this as very different from grinding. Herschel had believed that the final polishing was merely a very fine grinding, the direct continuation of the process by which, using finer and finer grades of emery, the outstanding irregularities of a surface are worn away by the actual removal of material. Beilby showed, however, more especially with regard to the polishing of speculum metal, that the polishing action consisted, in part, of a flowing action which would cover over the irregularities of the surface. The skin of the material, he concluded, owed its nature and stability in all cases to the surface tension, a conclusion markedly different from that of Lord Rayleigh, whose view in 1901 was that the polishing of glass consisted in an almost molecular wearing away of the highest parts of the surface, and who had supported this view by proving that a thickness of glass equivalent to six wavelengths of light (about 1/10,000 inch. —Ed.) was removed during the polishing, as distinct from the fine grinding process.

"J. W. French, writing in 1916 (*Transactions Opt. Soc.*, Vol. 17, page 24), suggested that the surface layer of a polished piece of glass consisted of a portion which had been caused to flow, more or less, under the strong surface forces of the polishing operation. This layer, which he termed the 'Beta layer,' was considered, from evidence based on the study of fire cracks, to be about eight wavelengths deep.

"In more recent work by the British Scientific Research Association the depth of the deepest pits in a finely ground surface was examined microscopically. The results showed that irregularities of the order of six to eight wavelengths or more are present in such surfaces, thus indicating again that polish is only complete when the surface is removed to the depth of these deepest pits, when Lord Rayleigh's observation is borne in mind.

"F. W. Preston, in 1921 (*Transactions Opt. Soc.*, Vol. 23, page 141), ex-

pressed the view that the surface of finely ground glass is of the nature of a 'flaw-and-fissure complex'; in other words, the surface skin is a layer of finely 'cracked' material. The polishing action would then consist in the removal of the fissure complex. In such a 'grey' surface there are probably (so it is suggested) a certain proportion of fine cracks slightly wedged open by the displacement of parts of the material. This is a possible cause of the strain first observed by Twyman (*Proceedings of the Optical Convention of 1905*, page 78—same address as Opt. Society; this is a book, not a periodical.—Ed.). The action of polishing allows these fissures to close up; when their width becomes much smaller than a wavelength of light they cease to be visible."

In contradistinction to the various molecular flow theories of the majority of British theorists, Dr. Elihu Thomson states below his theory of the nature of the polishing operation. Dr. Thomson is Director of the Thomson Research Laboratory of the General Electric Company at Lynn, Mass., where fused quartz was developed and is made; he has been an amateur worker in glass for 60 years, has also made optical surfaces of diamond, and has made objective lenses up to 10 inches in diameter. His theory is reprinted, by permission, from *the Journal of the Optical Society of America and Review of Scientific Instruments*, Vol. 6, No. 8, October, 1922. He states:

"The problem of how it is that, for example, a glass surface which has been smoothed or finely ground can, by proper means, be polished not only so as to be invisible ordinarily, but so that under the severest tests it shows no diffusion of light (as of the sun's rays falling on it) has at times engaged the attention of the ablest physicists. The late Lord Rayleigh studied the matter and his paper (Lord Rayleigh, *Proc. Roy. Inst. Gr. Britain*, March, 1901; *Trans. Opt. Soc.*, 19, Oct. 1917) on the subject is well known. He properly explains the polishing process on the principle of removal, by a process similar to grinding, of the high points of the surface, and progressively so until the whole ground surface has been cut away, but the cutting is by an action so fine that the grain produced is beyond the power of resolution by a microscope or other powerful optical means.

"It is the purpose here to show that while this view is measurably correct it does not go far enough, and that the polishing is a unique mechanical process; a self-regulated planing down of the surface to a real level without even the finest scratches or other character which would lead to diffusion of any light falling on the surface.

"Some have most erroneously tried to explain the result of the process, by assuming that the glass has, during the polishing, actually flowed; or that there was some peculiar plastic condition brought about which allowed the glass surface being polished to take on the characteristics of a liquid surface. There is no need for such hypotheses and no validity in such assumptions. This will be made clear.

"In burnishing of plastic metals by a hard burnisher there is, of course, such flow, but with hard, brittle, non-malleable materials like glass the process is decidely not like burnishing.

"Glass may receive an optical polish in either the wet or dry way. Other

materials of a brittle, non-malleable nature are dealt with similarly; such are quartz, agate, calcspar (Iceland), and many jewels and minerals.

"In the manufacture of plate glass the ground surfaces (the last, or smoothing stage, being often called *mud ground*) are not worked by grinding to so fine a grain of surface as in the better class of accurate optical work, and the polishing is done by runners of felt charged with rouge (crocus) and water moved over the plate by machinery. The result is that the surface obtained is not an optical one; it has a smoothness and polish similar thereto, but is wavy throughout, as can easily be discerned by a skilled eye in regarding the reflection of an edge from such surface; and, of course, by other simple tests. It is neither optical in the large or small elements of surface. The yielding felt runners have swept out indiscriminately the hollows, small and large, and have not held the surface to a definite figure. Similar yielding polishers are used in finishing the very irregular surfaces of cut glass. The cheaper kind of lenses, where accuracy of figure is not needed, are often cloth polished, a process which, if carefully conducted, gives a result intermediate between the plate glass surface and the true optical surface, such as is obtained by a pitch polisher with rouge and water. The considerations as to the true nature, the mechanics, of the polishing process are applicable to all such cases, but will be given in connection with the pitch polishing, most usual in good work. They apply, too, to the case of dry or paper polishing with paper-faced tools charged with tripoli (diatomaceous earth), a method of polishing which has been used to some extent in France for medium grade lenses.

"In rouge polishing with pitch for a carrier, as is usual, the surface of the pitch is moulded to fit the glass and is divided (usually) into small square facets by grooving. It is worked over the glass, or the glass worked upon it, by movement in all directions or such innumerable paths are given that no definite course is repeated. This is essential to the best result.

"The conditions as found, in successful work, are as follows: The rouge, though very hard, is friable and breaks down to a very fine powder. Too hard (non-friable) rouge will tend to fine scratches. These scratches are not like grinding or crushing, but are smooth-bottomed grooves, discoverable by a magnifier.

"The pitch is at all times yielding. It is made so by tempering and testing. If too hard, it tends to cause fine scratches all over the surface which is being polished. These, with very hard pitch, may resemble grinding, but ordinarily they show no crushing, but are smooth cuts.

"In grinding, on the contrary, the surface is crushed, while in polishing it is clean cut. Smooth cutting is the rule. The polishing is indeed a kind of planing process; the particles of rouge set themselves into the pitch surface and cut smoothly; they do not roll or grind. There are millions of fine planing or cutting edges at work fixed in position by becoming, at least temporarily, embedded in the pitch surface, which readily yields to receive them. They make smooth cuts as can readily be seen by examination of the scratches when the pitch is overhard or the rouge too hard and non-friable. Good rouge is friable without apparent limit, and rouge washed out of a used polisher may be so fine as to float for days in colloidal solution.

"All the above considerations are fairly well known and recognized, but there is one additional condition or circumstance which, so far as the author knows, is worthy of record, no attention having been hitherto drawn to it.

"It is this: by the very nature of the case the particles which are doing the cutting in polishing are all *automatically adjusted*, in successful work, to cut to the *same depth* during any stroke. The yielding nature of the pitch surface not only ensures this, but makes it a necessary consequence, for any particle of rouge riding higher than another is at once depressed to the proper level by sinking into the pitch surface. The innumerable cutting edges of all the particles reach a common level, and with motion of the polisher in all directions, and cutting smooth (no crushing or grinding) the result cannot fail to be what it is, an optical surface without grain or irregularity. The rouge is friable without limit, so that the polishing particles may, in the process, become finer and finer. With felt, cloth or paper as a carrier for the polishing powder, the effect is much the same; the particles are held to position when cutting, as planing tools. Even fine washed carborundum will polish glass if held in the surface of soft wood or cork, and the author has even produced a fair polish on a glass lens by a soft metal tool charged with fine carborundum. In such case, the polishing takes place in a few seconds, but the technical difficulties are very great. In dry polishing, a sheet of paper is pasted down on the surface of the polishing tool, and a special high-grade pure paper, rather heavy and uncalendered, is used. This is charged by gently rubbing its surface with a lump of fine tripoli selected for the purpose, the fine silicious skeletons composing which constitute the polishing powder. The first application to the smoothed surface, as of a lens, which surface has the fine grain usual in such a case, is to show innumerable fine scratches, criss-crossing in every direction. They are, however, smooth scratches. As the work goes on, the tripoli works down to finer and finer conditions, while the polishing comes up gradually, no new application of the powder being required after the start. It is manifest that here, too, is the condition of smooth cutting and particularly a self-adjustment of cutting depth, owing to the yielding character of the paper surface, so that at the end all the cutting is done in one surface of movement. It is believed that this dry paper process is much less used than formerly. It cannot be expected to yield the high accuracy that may be obtained with the wet pitch.

"It is thought that in pointing out the mechanics of the polishing process, and more especially the smooth cutting and self-adjustment of cutting particles above described, the interesting process of the production of an optical surface may be relieved of something of the mystery which has been its accompaniment.

"The author has drawn upon an experience of more than fifty years in occasional working of optical surfaces on glass of many kinds and on media, such as crystal quartz and fused quartz, Iceland spar and others.

"The amount of material removed from the surface under treatment is, of course, seen to be almost infinitesimally small per stroke, and it is only by the long continuance of this action that at last there is a sufficient removal to secure an optical surface. Time is saved by carrying the fine grinding or smoothing as far as possible before applying the polisher. As Rayleigh has

stated, and it is, of course, the common experience, polishing begins on the highest or most elevated parts of the surface, seen only under a magnifier, and these are removed while the polished spots widen out, and, if the surface has been well prepared, or *bottomed,* as it is termed, spread to include the whole surface. If the surface has not been well bottomed there will remain pits which the slow planing action of the polisher is incompetent to remove in reasonable time, and if the polishing is continued too long the surface is more than likely to have lost its truth, or has been seriously deformed. This, however, depends on the polisher itself keeping its form. Too soft pitch is a guard against polisher scratches from particles of grit, but not conducive to accuracy. Accuracy can be helped by remoulding the polisher at intervals by slight warming of its surface and application to a true surface of the same character as that being produced, while moistening the said surface to prevent adhesion.

"No matter what degree of smoothness has been attained in polishing, the continued smooth removal of the glass surface goes on as long as there is rouge, pitch and water applied; a fact which is, of course, taken advantage of in parabolizing a concave astronomical glass mirror."

In addition to the references to the back files of the *Transactions of the Optical Society,* quoted above, the scientifically inclined amateur will find valuable material in the same periodical, No. 1 of Volume 18 (1917), "More Notes on Glass Grinding and Polishing," by James Wier French; also in Volume 19 (1917), No. 1 (Oct.), "Polish," by Lord Rayleigh; and in No. 3 for 1925-26, pages 181-189, Preston on "Nature of the Polishing Operation." See letter in *Nature,* London, Sept. 4, 1926, page 339.

H. Dennis Taylor, of Taylor, Taylor and Hobson, Ltd., states in *Transactions of the Optical Society,* Volume 21, page 82, "If the rouge imbeds itself thoroughly in the pitch surface where it touches the glass, so that the said surface appears of a rich orange red, *not* glazy when dry, but of a matt surface, then we always know that both the polishing and figuring are going on satisfactorily. In hand polishing the sweetness and evenness of the frictional resistance is then most noticeable, whereas if the pitch surfaces in contact with the glass appear to be glazy in appearance when the polisher is dry, we know that the polishing and figuring are not going on satisfactorily; we then expect trouble and generally get it. In the case of hand polishing, a polisher in this condition is apt to suck and only move in jerks.

"Still worse is it when the pitch surface in contact with the glass refuses the rouge and shows a black, glazy appearance; then we usually get the glass covered with fine scrubs, while it refuses to take a good figure. This sort of polisher clings hard to the glass and can only be moved by hard jerks."

To The Editor, at least, this statement by Taylor would seem to bear out Dr. Elihu Thomson's theory of polish. While it is possible to polish an optical, glass surface on a pitch lap from which the rouge has been washed, an attempt to do this with a lap which has never been armed with rouge will possibly prove illuminating.

Transactions of the Optical Society, No. 3 for year 1922-23, contains an article on the properties of pitch, by F. W. Preston. The Editor has already made numerous references to the *Transactions,* which are not, however, mainly devoted to telescope making, as might logically be inferred from these references. The articles mentioned are the few of that nature which were found while going systematically through all the back files.

Herschel's Mirrors: In *Transactions Optical Society,* No. 4 for 1924-25, Dr. W. H. Steavenson, F. R. A. S., outlines a "Peep into Herschel's Workshop." Sir William Herschel left four complete volumes in manuscript, relating to his various processes and experiments, in which he sums up the results of 40 years of experience in the art of telescope making. These manuscripts are now in the hands of the Royal Astronomical Society, and, says Dr. Steavenson, "it is greatly to be desired that means should some day be found for publishing them." (Here is an opportunity for some generous amateur enthusiast or group of enthusiasts.—Editor.) The same issue describes and illustrates Herschel's many mirrors, eyepieces, etc., which are still in possession of his granddaughter, Miss Francisca Herschel. Herschel did not use the knife-edge test, because Foucault had not yet hit upon it. He worked by feeling and by a remarkable sense of intuition. Some of his mirrors had been soldered down in cans prior to his death in 1822. Opened in 1924, a century later, they were found to be splendidly polished and without a trace of tarnish! Most of them were found to be over-corrected and to have two or three zones, yet on the whole the figure of all the mirrors was up to a very fair standard, and it is probable, says Dr. Steavenson, that they performed quite well in actual use. The complete report is extremely interesting. Think of the thrill of opening up cans containing mirrors sealed up 102 years previously by Herschel and testing the work of this great master, for the first time, under the knife-edge!

First Announcement of Foucault Test: True devotees to the ancient and honorable art of telescope making may discover real interest—though no new information—in a holy pilgrimage to some large library to look up the first publication, in 1859, of information concerning the famous Foucault test with the knife-edge. They will find it in a long paper by Foucault himself, safely ensconced in Volume 5 of the *Annales de L'Observatoire Impérial de Paris,* pages 197 to 237, and entitled "Mémoire sur la Construction des Télescopes en Verre Argenté." Do not miss the incomparable engravings in the back of the volume, showing the characteristic shadow of ellipse and paraboloid and the theory of the test. After studying these engravings and reading Foucault's lucid account it will become evident that he did not rush into print until he had both theory and practice of the new test well worked out. A rather rare old book entitled *A Compleat System of Opticks,* Cambridge, England, 1738, by Robert Smith, describes on page 310 a test which is really the eyepiece test but which bears certain superficial resemblances to Foucault's test. The test was devised by John Hadley, inventor of the sextant. After reading Robert Smith's description of it, one is struck by the fact that Hadley, had he gone on experimenting, might have blundered on the knife-edge test 75 years before it was actually discovered by Foucault. How Herschel would have thanked him!

The Objective Lens: We have previously omitted from this book mention of objective lens making because we wish to confine our interest as far as possible to a single effort, the encouragement of reflecting telescope construction, rather than to attempt to spread over broader territory; also because in the average case the objective lens is not a very suitable work for the amateur—certainly not, at any rate, for the beginner. Some, however, who may have successfully completed several mirrors and who happen to be "born artists" (see page 89) may succeed at this job, though it is well to approach it with due humility unless one expects nothing better than a mediocre job. In making an objective lens there are four surfaces to figure instead of one, and attempting this job without first having made a few mirrors would be like attempting to do the "grapevine" before one had learned to stand up on skates. In a private communication Ellison writes: "There is no doubt that the making of an objective lens is a job to tax the abilities of the most expert. Yet, knowing what I do of your enterprising countrymen, I felt sure that, given the information, there would be a considerable number anxious to attempt the task, and that a certain proportion of these would attain to success." The literature on the subject is scarce. A brochure giving curves for a single type of lens (for a 1-inch finder telescope), previously calculated and ready to use, may be purchased from John M. Pierce, and a second brochure tells how to make a simple eyepiece. Specific instructions for computing the radii of an achromatic objective (5-inch) by Charles L. Woodside appeared in the *Scientific American Supplement*, Dec. 11, 1897. This is out of print, but can be found in library files. Condensed instructions by means of which the physicist may design his curves are contained in *Letter-Circular* 67, U. S. Bureau of Standards, Washington, D. C., gratis. A more abstruse theoretical discussion of the same nature appears in the *Transactions of the Optical Society* for May, 1919. Neither this nor the Bureau of Standards circular above mentioned gives practical instructions for proceeding with the actual work. *Popular Astronomy*, May, 1926, contains an article by Loren S. Noblitt giving brief, practical instructions. By far the best of all, however, is the original Ellison book treatise, now revised by the author and included in Part II of the present volume.

Astronomical Photography: Those who wish to try astronomical photography should obtain a little book called *Astronomical Photography for Amateurs*, by H. H. Waters. Professor Edward Skinner King of Harvard College Observatory, deceased in 1932, wrote a treatise on this subject, in which he embodied the whole of his lifetime experience in the same field. He was a widely-known authority. He also asked that mention be made of the *Autobiography of John Brashear* as an incentive to amateur workers, particularly in view of Brashear's early struggles to produce his first mirror, his patience and his persistence. Brashear began as an amateur, found he could make good mirrors, advertised his work in the *Scientific American* (Oct. 30, 1880), and after a long career made the great 72-inch mirror of the Dominion Astrophysical Observatory at Vancouver, B. C. Returning to astronomical photography for amateurs, Latimer Wilson has done successful work of this kind, and has published two articles on it in *Popular Astronomy* (May, 1926; Aug.-Sept.,

1927). In *Popular Astronomy*, Jan., 1926, page 69, Robert Ellms of Baldwin-Wallace College tells how he took astronomical photographs with an ordinary Kodak, using film.

Harold A. Lower has taken some excellent lunar photographs with a 6-inch reflector, superspeed Eastman cut film and simple equipment.

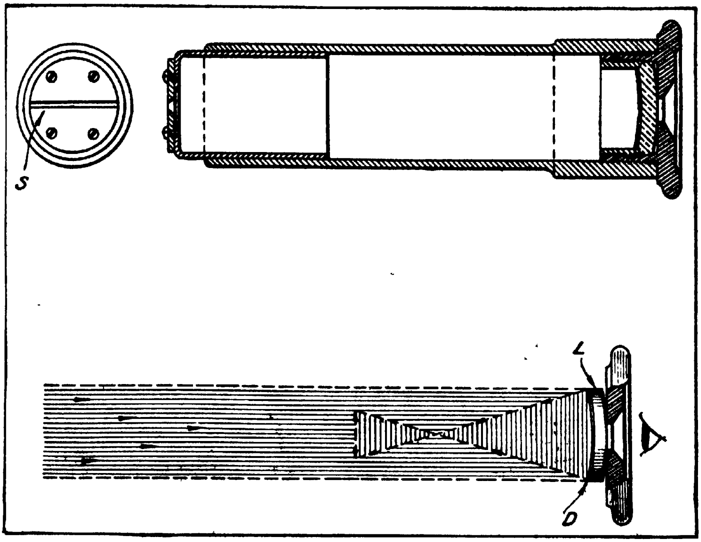
In the *Journal of the British Astronomical Association*, Jan., 1928, F. J. Sellers, F. R. A. S., summarizes in three pages the work of lunar photography with small telescopes. He has done considerable research in that direction and the article contains in compact form the results of this research.

LUNAR PHOTOGRAPH TAKEN WITH A REFLECTOR

Made by Latimer J. Wilson with an 11 inch mirror and a Cramer contrast plate. Enlarged on a positive lantern plate, and contact negative made from that. The grain is due to the forced development to bring out the terminator. Wilson also uses Hammer press plates (ultra rapid—about 750—H. and D.) or special double coated Ortho plates.

Small Spectroscopes for use with telescopes are not highly satisfactory except when used with a fair-sized light gatherer—something larger than a 6-inch mirror, or even a 10-inch. They will show certain prominent lines in the spectra of first magnitude stars when the atmosphere is clear. In the *Scientific American*, December, 1926, Ernst Keil, maker of scientific instruments, briefly described a small spectroscope. His drawing, on the opposite page, virtually explains itself. *S* is the slit; *L* is the eyepiece lens, a common concavo-convex spectacle lens rounded on an emery wheel and worked to focal length of about 8 inches; *D* is the transmission grating, a piece of transparent replica

from a diffraction grating (can be obtained from Central Scientific Supply Co.—Ed.). The replica is thin celluloid containing the grooves and is mounted on glass. Peel it off carefully and place it on the concave side of the lens. In *Popular Astronomy,* March, 1926, Jack Garrison described a small rig for solar spectroscopy. A. R. Dunlop states that he constructed for a few dollars a very efficient, simple spectroscope, using a replica grating, which gives fairly good views of solar prominences with a 2½-inch refractor. Carl Zeiss, Inc., sells a small spectroscope; also John Browning, Ltd.

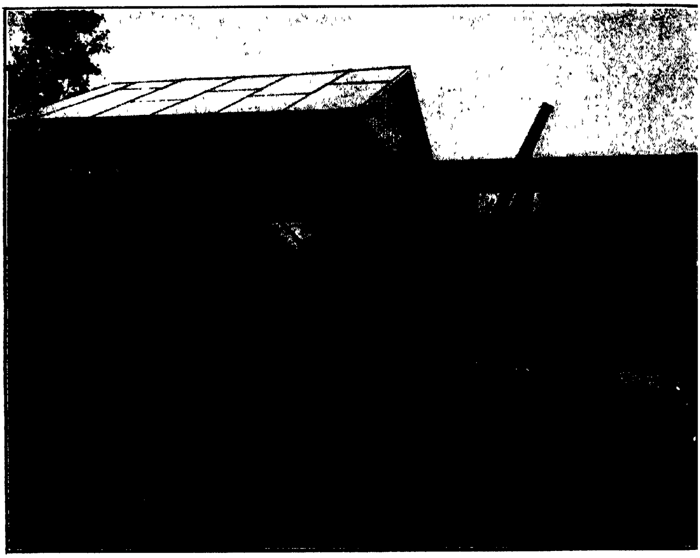


A SIMPLE, HOME MADE SPECTROSCOPE

Still another type is described in Barns' "1001 Celestial Wonders."

Observatories: Literature on observatories is scarce. See Bell, *The Telescope,* which describes several. In *Popular Astronomy,* May, 1922, J. Ernest G. Yalden described an observatory for a 9½-inch reflector, with pyramidal revolving roof. He also described another small refractor dome in *Popular Astronomy,* October, 1920. William Braid White described a revolving dome (tin) observatory of small size, in *Popular Astronomy,* October, 1916. Charles Early described in *Popular Astronomy,* October, 1914, a tin-domed housetop observatory. A small, brick-walled observatory with dome was described in *Popular Astronomy,* issue for June-July, 1913. A small turret reflector of

unique design, combining in one structure the telescope mounting and observatory was described in *Popular Astronomy*, Aug.-Sept., 1927. In general, it is best to avoid complicated curved domes and stick to straight lines. One of the best of all types of "observatories" (actually it is only a housing) consists of an ordinary barn-like structure mounted on rollers on a track. During observation this "barn" is rolled away entirely, leaving the telescope in the open. Better yet, one may place the rollers and track at the plate level of the structure and merely slide aside the roof. These types require plenty of room.



A SIMPLE, STRAIGHT LINE OBSERVATORY

The roof rolls off the walls on tracks at the plate level. A little practical experience in building the conventional hemispherical dome for an observatory will speak loudly in favor of the straight line type which is free from the "fusswork" involved in fitting materials to curved surfaces.

The following seven pages of discussion of sidereal time and the use of setting circles were contributed by R. Newton Mayall, Boston landscape architect, and Margaret Walton Mayall, Research Assistant at the Harvard College Observatory (the authors of nine articles on sun-dial design, *Scientific American*, Feb., 1934, to March, 1935). The discussion is supplementary to the matter in Chapter VI, page 46.

Calculation of Sidereal Time and Setting the Circles, By R. Newton Mayall and Margaret Walton Mayall, M.A.): An equatorial mounting with declination and hour circles will greatly facilitate the use of a telescope. With such an equipment the amateur can emulate the professional astronomer, who depends entirely upon these circles and sidereal time to set his instruments—especially those without finders. "Sweeping" the sky to locate an object is abolished by the proper use of the circles and sidereal time.

Few realize that we have in use today no less than five types of time. A critical discussion of the various kinds of time will be found in any good astronomical textbook, or at the back of the American Ephemeris and Nautical Almanac. The Ephemeris is published each year by the Government, and it may be obtained from the Superintendent of Documents, Washington, D. C. However, one does not need to know all about the various kinds of time in order to use and enjoy his telescope; but if he wishes to handle his telescope to the best advantage he would naturally make use of sidereal time (star time), and know how to obtain it.

Sidereal time is measured by the daily motion of that point on the celestial equator called the Vernal Equinox, from which the right ascension of celestial bodies is measured. Thus a sidereal day, at a given place, is the interval of time between two successive upper transits of the Vernal Equinox across the meridian of that place; and sidereal time is reckoned consecutively from 0^h to 24^h.

The best method of computing sidereal time, where great accuracy is desired, is by the use of the formulas and tables given in the current Ephemeris. Rarely is it necessary to use time to the nearest hundredth or even tenth of a second, and seldom is it necessary to worry about getting things down to the nearest second; and in most cases the nearest minute will be sufficient.

Since many readers will not have access to any of the many Ephemerides published, the formula for computing sidereal time is given here, together with the two necessary tables.

The sidereal time for a given place and date is found by the following formula, where L.M.T. = local mean time; Sid.T. = sidereal time; and G.C.T. = Greenwich civil time.

SID.T. = L.M.T. + SID.T. for 0^h G.C.T. + CORRECTION for G.C.T.

This may seem complicated, but after two or three attempts it will be found extremely easy to solve, and quicker than other methods; because two of the values are derived by means of constants, and the others are obtained directly from the tables. By computing sidereal time, a watch can be set before darkness, thus leaving more time to be spent on actual observation.

The *local mean time* at a given place is found by adding or subtracting, from the standard time of the locality, 4^m of time for each degree of longitude * by which the place is located east or west of its standard time meridian.

* The longitude is best obtained from the topographic maps of the U. S. Geological Survey. These maps are drawn on sheets about 16½" x 20", at various scales. The latitude and longitude can be obtained from them accurately to within 1 to 5 seconds of

If the place is east, the difference is added to the standard time; if west, it is subtracted.

The standard time meridians (S.T.M.) in the United States are:

75th = Eastern Standard Time (E.S.T.) = 5^h W. of Greenwich
90th = Central Standard Time (C.S.T.) = 6^h W. of Greenwich
105th = Mountain Standard Time (M.S.T.) = 7^h W. of Greenwich
120th = Pacific Standard Time (P.S.T.) = 8^h W. of Greenwich

EXAMPLE: Find the local mean time at Cambridge, Mass., at 9:30 p.m. E.S.T. The longitude of Cambridge is 71°07′30″W. of Greenwich, which, if expressed in time, would be $4^h44^m30^s$W. In other words, Cambridge is 15^m30^s east of its standard time meridian (the 75th). From the following formula we find that at Cambridge, 9:30 p.m. E.S.T., the corresponding local mean time is equal to 9:45:30 p.m.

Standard Time ± Diff. in long. from S.T.M. = Local Mean Time
9:30 p.m. E.S.T. + 15^m30^s = 9:45:30 p.m.

Greenwich civil time may be found by adding to or subtracting from the standard time of a place, the number of hours its standard time meridian is west or east of Greenwich. If the place is west of Greenwich the quantity is added; if east, it is subtracted.

EXAMPLE 1: To find the Greenwich civil time corresponding to 4:30 p.m. E.S.T., at Cambridge, Mass., on May 15, we would add 5^h (the S.T.M. for Cambridge is the 75th, or 5^hW. of Greenwich), which would give us 9:30 p.m. G.C.T., on May 15.

EXAMPLE 2: Suppose it is 9:30 p.m. E.S.T. at Cambridge, on May 15. In this case we add 5^h and get 14^h30^m G.C.T.; but this would be after midnight, so 12^h must be subtracted. Thus, the G.C.T. would be 2:30 a.m. on May 16 (the following day).

The *sidereal time for 0^h Greenwich civil time* is given in Table I, to the nearest minute, for each day in the year. This table is a mean table, and it is subject to a maximum variation, at times, of about two minutes.

The *correction for Greenwich civil time* is given in Table II. This correction must be made in order to convert a mean time interval into sidereal time; and in the formula, the mean time interval is Greenwich civil time (that is, the numbers of hours that have elapsed since 0^h G.C.T.).

EXAMPLE: If our Greenwich civil time happens to be $15^h37^m45^s$, the correction would be 2^m34^s. From Table II the correction

for 15^h	= 2^m28^s
for 37^m	= 0 06
for 45^s	= 0 00
Total correction	= 2^m34^s

arc. Index maps for each state, showing the areas for which topographic maps are available, may be procured gratis. The larger stationery stores throughout the United States generally carry these maps in stock, at nominal prices, or they may be procured by writing to the Director, U. S. Geological Survey, Washington, D. C.

Three examples are given below, showing not only the use of the above formula for finding sidereal time, but also what happens in the computation at different times of day.*

EXAMPLE 1: At 9:30 p.m. E.S.T., May 15, Cambridge, Mass.—Find the sidereal time. (Long. of Cambridge = 71°07′30″W., or $4^h44^m30^s$W.)

Local mean time, at Cambridge, May 15, 21^h30^m E.S.T. (9:30 p.m.)	= $21^h45^m30^s$
Sidereal time for 0^h G.C.T., May 16 (Table I)	= 15 32
Correction for 2^h30^m G.C.T. (Table II)	= 0 00 25
Sidereal time	= $37^h17^m55^s$
Deduct	— 24 00 00
The required Sid. time	= $13^h17^m55^s$
	or = 13^h18^m

EXAMPLE 2: At 1:25 a.m. C.S.T., July 19, Chicago, Ill.—Find the Sidereal time. (Long. of Chicago = 87°37′30″W., or $5^h50^m30^s$W.)

Local mean time, at Chicago, July 19, 1^h25^m C.S.T. (1:25 a.m.)	= $1^h34^m30^s$
Sidereal time for 0^h G.C.T. July 19 (Table I)	= 19 44
Correction for 7^h25^m G.C.T. (Table II)	= 0 11 13
The required sidereal time	= $21^h19^m43^s$
	or = 21^h20^m

EXAMPLE 3: At 6:15 a.m. P.S.T., Sept. 23, at a place whose longitude is 123°10′45″W. ($8^h12^m43^s$W.)—Find the sidereal time.

Local mean time, at 123°10′45″W. long., Sept. 23, 6^h15^m P.S.T. (6:15 a.m.)	= $6^h02^m17^s$
Sidereal time for 0^h G.C.T. Sept. 23 (Table I)	= 0 06
Correction for 14^h15^m G.C.T. (Table II)	= 0 02 20
The required sidereal time	= $6^h10^m37^s$
	or = 6^h11^m

Now that we know how to obtain sidereal time, what good is it? What do we do with it? How is it used in conjunction with the telescope?

The positions of celestial objects are located in a manner similar to that of places on the earth. The location of a place is determined, on the earth,

* The computer will find it much easier if he converts his standard time and local mean time into astronomical terminology, at the outset; that is, instead of saying May 15, 9 30 p.m., add 12 hours and call it May 15, 21^h30^m. Remember that the astronomical day begins at midnight and the hours are numbered consecutively, from 0^h to 24^h. If this is done, mental work, errors, and worry are lessened, and it is only necessary to deduct 24^h at the end of the computation if the required sidereal time is greater than 24^h. (See Example 1.)

when its latitude and longitude are known. The astronomer's latitude is called "declination" and his longitude is referred to as "right ascension." (See page 46.)

The declination circle on a telescope is so placed that its plane lies perpendicular to the plane of the equator; and each quadrant on its periphery is divided into degrees and minutes of arc, from 0°–90°.

The hour angle circle is so placed that its plane lies at right angles to the plane of the declination circle, and each quadrant on its periphery is divided into hours and minutes of time, from 0^h–6^h. The hour angle of a celestial object is its distance in time from the observer's meridian; thus, the hour angle of any celestial object may be read directly from this circle.

The declination and hour angle circles are so arranged that each reads 0, when the telescope is pointed due south and its optical axis lies in the plane of the meridian. So placed, the telescope points to that point where the plane of the observer's meridian intersects the celestial equator.

Therefore, in order to set our telescope on an object invisible to the naked eye, whose right ascension and declination are known, we must first set the telescope to the proper declination and clamp it; then find the hour angle of the particular object in relation to the observer's meridian; then turn the telescope toward the east or west, as the case may be, so that the reading of the hour circle is equal to the hour angle of the object at any particular time.

If sidereal time and the right ascension of an object are known, the hour angle is found by subtracting the smaller quantity from the larger. If the R.A. is greater, the hour angle is east; if the sidereal time is greater, the hour angle is west.

EXAMPLES: Sidereal time	$= 13^h18^m$
R.A. of R Ursa Majoris	$= 10\ 40$
Hour angle	$= 2^h38^m$ W.
R.A. of M13 in Hercules	$= 16^h40^m$
Sidereal time	$= 13\ 18$
Hour angle	$= 3^h22^m$ E.

Warning! When looking up the position of a celestial body, for use in the above computations, be sure that the Epoch of the position given is not more than 10 or 15 years before or after the date of observation. More distant Epochs may result in serious error, due to the precession of the equinoxes.

The methods outlined above for computing sidereal time and setting the telescope are used by the professional astronomer. Now let's do it a different way, which, although not so accurate, will serve one's purpose equally as well. Since sidereal time for a given place is equal to the right ascension of an object when it is on the meridian of that place, it is only necessary to pick out some bright object whose R.A. is known, which is on or near the equator, east of and in close proximity to the meridian of the place. Then set the

scope due south and clamp it in declination (that is, at the declination he object selected). Knowing the right ascension of the object (this ıld be obtained from the current Ephemeris), watch the field of view, when the object arrives at the center of the field, set a watch or clock gree with the R.A. of the object. [This watch or clock then becomes equivalent of the slip ring described in Part III.—*Ed.*] If a watch is l, whose dial is divided into 12 hours, it is necessary to deduct 12 from R.A. when the R.A. is greater than 12 and then set the watch to agree the remainder, always remembering that 12 hours must be added to reading of the watch when using it.

nother simple method of finding sidereal time is to set the telescope fully on some easily distinguished bright object such as Sirius, which ot too far removed from the celestial equator and whose R.A. (this should btained from the current Ephemeris) is known. When it is in the center he field of view, the hour circle will show the hour angle of the object, he time which has elapsed (or must elapse) since (or before) it crossed observer's meridian. If the object is east of the meridian, the sidereal is obtained by subtracting the hour angle of the object from its R.A.; if the object is west of the meridian the sidereal time will be obtained dding the hour angle to the right ascension.

here is also another method of finding an object invisible to the naked which does not require the use of sidereal time. First, set the telescope ome well known bright star whose R.A. is known. Find the difference 'een the R.A. of the bright star and the object sought. Add or subtract difference in R.A. to or from the hour angle shown on the hour circle. ıe object sought is nearer to the observer's meridian than the bright star, difference in R.A. is subtracted from the hour angle of the bright star; ıe bright star is nearer the meridian, the difference in R.A. is added. gives the hour angle of the object sought, and if the telescope is set hat hour angle and the proper declination, the object should be found oximately in the center of the field of view.

TABLE I

Sidereal Time for 0^h Greenwich Civil Time

Compiled from the *American Ephemeris*.

Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	$6^h 40^m$	$8^h 42^m$	$10^h 32^m$	$12^h 35^m$	$14^h 33^m$	$16^h 35^m$	$18^h 33^m$	$20^h 36^m$	$22^h 39^m$	$0^h 37^m$	$2^h 39^m$	$4^h 38^m$
2	6 44	8 46	10 36	12 39	14 37	16 39	18 37	20 40	22 43	0 41	2 43	4 42
3	6 48	8 50	10 40	12 43	14 41	16 43	18 41	20 44	22 47	0 45	2 47	4 45
4	6 52	8 54	10 44	12 46	14 45	16 47	18 45	20 47	22 51	0 49	2 51	4 49
5	6 56	8 58	10 48	12 50	14 49	16 51	18 49	20 51	22 55	0 53	2 55	4 53
6	7 00	9 02	10 52	12 54	14 53	16 55	18 53	20 55	22 59	0 57	2 59	4 57
7	7 03	9 06	10 56	12 58	14 57	16 59	18 57	20 59	23 02	1 01	3 03	5 01
8	7 07	9 10	11 00	13 02	15 01	17 03	19 01	21 03	23 06	1 05	3 07	5 05
9	7 11	9 14	11 04	13 06	15 04	17 07	19 05	21 07	23 10	1 09	3 11	5 09
10	7 15	9 18	11 08	13 10	15 08	17 11	19 09	21 11	23 14	1 13	3 15	5 13
11	7 19	9 21	11 12	13 14	15 12	17 15	19 13	21 15	23 18	1 17	3 19	5 17
12	7 23	9 25	11 16	13 18	15 16	17 19	19 17	21 19	23 22	1 20	3 23	5 21
13	7 27	9 29	11 20	13 22	15 20	17 22	19 21	21 23	23 26	1 24	3 27	5 25
14	7 31	9 33	11 24	13 26	15 24	17 26	19 25	21 27	23 30	1 28	3 31	5 29
15	7 35	9 37	11 28	13 30	15 28	17 30	19 29	21 31	23 34	1 32	3 35	5 33
16	7 39	9 41	11 32	13 34	15 32	17 34	19 33	21 35	23 38	1 36	3 38	5 37
17	7 43	9 45	11 36	13 38	15 36	17 38	19 37	21 39	23 42	1 40	3 42	5 41
18	7 47	9 49	11 39	13 42	15 40	17 42	19 40	21 43	23 46	1 44	3 46	5 45
19	7 51	9 53	11 43	13 46	15 44	17 46	19 44	21 47	23 50	1 48	3 50	5 49
20	7 55	9 57	11 47	13 50	15 48	17 50	19 48	21 51	23 54	1 52	3 54	5 53
21	7 59	10 01	11 51	13 54	15 52	17 54	19 52	21 55	23 58	1 56	3 58	5 56
22	8 03	10 05	11 55	13 57	15 56	17 58	19 56	21 58	00 02	2 00	4 02	6 00
23	8 07	10 09	11 59	14 01	16 00	18 02	20 00	22 02	00 06	2 04	4 06	6 04
24	8 11	10 13	12 03	14 05	16 04	18 06	20 04	22 06	00 10	2 08	4 10	6 08
25	8 14	10 17	12 07	14 09	16 08	18 10	20 08	22 10	00 13	2 12	4 14	6 12
26	8 18	10 21	12 11	14 13	16 11	18 14	20 12	22 14	00 17	2 16	4 18	6 16
27	8 22	10 25	12 15	14 17	16 15	18 18	20 16	22 18	00 21	2 20	4 22	6 20
28	8 26	10 28	12 19	14 21	16 19	18 22	20 20	22 22	00 25	2 24	4 26	6 24
29	8 30	......	12 23	14 25	16 23	18 26	20 24	22 26	00 29	2 27	4 30	6 28
30	8 34	......	12 27	14 29	16 27	18 29	20 28	22 30	00 33	2 31	4 34	6.32
31	8 38	......	12 31	.	16 31	...	20 32	22 34	.	2 35	..	6 36

TABLE II

Correction to Be Added to a Mean Time Interval to Convert Mean Solar into Sidereal Time

Hours			Minutes						Seconds	
Hrs.	Cor.		Min.	Cor.	Min.	Cor.	Min.	Cor.	Sec.	Cor.
1	0^m	10^s	1	00^s	21^m	3^s	41	7^s	1	$0^s.0$
2	0	20	2	0	22	4	42	7		
3	0	30	3	0	23	4	43	7	to	
4	0	39	4	1	24	4	44	7		
5	0	49	5	1	25	4	45	7	60	$0^s.2$
6	0	59	6	1	26	4	46	8		
7	1	09	7	1	27	4	47	8		
8	1	19	8	1	28	5	48	8		
9	1	29	9	1	29	5	49	8		
10	1	39	10	2	30	5	50	8		
11	1	48	11	2	31	5	51	8	Note: The correction for seconds is so small that it may be disregarded.	
12	1	58	12	2	32	5	52	9		
13	2	08	13	2	33	5	53	9		
14	2	18	14	2	34	6	54	9		
15	2	28	15	2	35	6	55	9		
16	2	38	16	3	36	6	56	9		
17	2	48	17	3	37	6	57	9		
18	2	57	18	3	38	6	58	10		
19	3	07	19	3	39	6	59	10		
20	3	17	20	3	40	7	60	10		
21	3	27								
22	3	37								
23	3	47								

Compiled from the Nautical Almanac (Great Britain)

That part of the Miscellany between pages 278 and 286 was written for the first edition, published in 1926; the part between pages 287 and the present page for the second edition, published in 1928; while the following notes were prepared in 1932 for the third edition.

Making Templates: The following is from a letter written by Prof. Elihu Thomson: "My method of making templates for the curves of lenses or mirror surfaces is very simple and effective as well as accurate. I make them of sheet glass (thin photo glass is best) by using a radius bar as usual on the floor with a glass cutter (glazier's diamond) set in at radius distance from pivot or center with diamond edge projecting at proper angle. A glass plate is thus marked by the diamond and if the cut is a real cut and not a scratch, the plate will break along the line quite nicely. To finish the pair it is only necessary to fine-grind the edge of the cut by laying them down on a flat surface (a board) and moving one on the other lengthwise, using fine Carborundum and water. Very rapidly the fit becomes perfect. Even greater accuracy is attained by reversing one of them so as to exchange ends. The edge, being now a fine-ground surface, can be marked or blackened by a lead pencil before applying it to the disk of the lens or mirror and it will mark (by slight end movement) the places of contact with the disk. I have even used this method with short curves, using very thin glass, with success. Of course for the best results near the finish I use a spherometer of usual three-legged pattern with micrometer screw in center."

Removable Handle for Mirror Disks: Several have discovered that rubber-cup sink clean-outs make excellent handles. When wet they are said to stick like a bulldog to a root (performance not positively guaranteed, however). These are the kind of rubber cups, attached to the end of a stick, which the plumber brings—or, rather, goes back for—when your sink traps become plugged. The smaller size, about three inches in diameter, is most suitable for the mirror worker. The handle may be sawed off. To attach, wet, apply to disk, and press hand on over side. To detach, press on opposite side.

Grinding Out of Doors will do no harm, regardless of temperature. In addition, it provides assurance that the coarser abrasives never will be brought near the indoor place where rouge is later to be used, and is therefore all in favor of freedom from scratches.

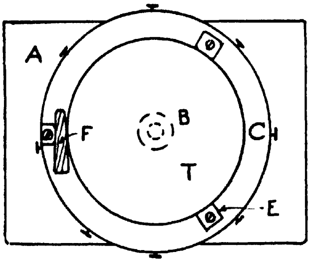
Refusal of the Mirror to Become Concave is a rather frequent difficulty among beginners. The cause is generally too rapid strokes. Workers who attempt to combine setting-up exercises or fat reduction with grinding will get exercise and fat reduction, but will discover a stubborn mirror disk, which will either become concave very slowly or not at all. Sixty cycles per minute—that is, across and back once a second—should be the speed limit, but even this is rather frantic. The habit of taking mirror making in low gear is in general a good mental discipline to acquire. It conduces to cautious, thoughtful workmanship.

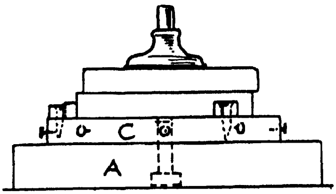
There is a reason why rapid strokes annul much or all of the normal concaving tendency of a mirror. At opposite ends of the stroke a mirror must each time be brought to rest and its motion reversed in direction. This

is done by force applied on the handle, above the center of mass of the mirror. But the momentum of the mirror tends to keep it moving in the same direction in which it has been moving. The resultant is that, under these two offset forces, it tends to ride up on edge. (It actually would, if the strokes were rapid enough.) This throws a share of its weight on the edge of the mirror and center of the tool, at the exact time when it is desired to accomplish just the opposite, *i.e.*, to abrade the center of the mirror and edge of the tool more than the other portions. Therefore little or no positive progress is made. This tendency increases directly as the height of application of effort, and as the square of the velocity of motion. When about one stroke-cycle per second is exceeded it begins to mount up rapidly enough to annul some of the desired concaving tendency, and at two stroke-cycles per second it will almost entirely offset that tendency.

Ideally, the effort should be applied at the center of mass of the disk, and then this tendency could not occur. Practically, a short handle (or none) will help. So will a reasonably deliberate attack on the job. The attachment, when a machine is used, may to advantage be a pin-and-socket or ball-and-socket low down, close to the face of the mirror.

A Convenient Grinding Stand which permits sitting down to work consists of a base *A* of heavy plank, with a center pin (an old bolt end) *B*, a wooden ring *C*, nails for ease in turning the tool, stops *E* if needed, and a wooden



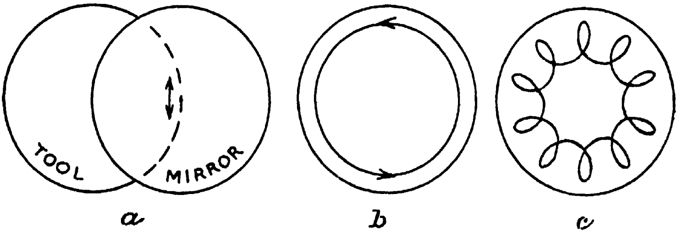


Drawings by Russell W. Porter, after James C. Critchett

wedge *F*. This was designed by James C. Critchett. It permits quick removal of the tool and quick inversion of tool and mirror but, because of the occasional need to invert, it must be used in connection with the rubber clean-out force-cup mentioned elsewhere as a handle for the mirror disk, or else with no handle. It will require careful cleansing after each grade of abrasive.

Strokes in Grinding: In addition to the more conventional 'cross-and-back stroke, several others are possible and are used more or less in various combinations by professional opticians, mainly for hogging out the rough curve without great loss of thickness at the edge. In *a* the center of the upper disk moves over the edge or near the edge of the lower one, as shown by the

arrow, which is its path during one stroke cycle. This represents only one position with regard to the pedestal; of course, the worker will shift gradually round the pedestal, just as in the more familiar method of grinding. In *b* the upper disk is swept round and round with its center always near the edge of the tool, or perhaps three-fourths way out. The arrows repre-



Drawings by Russell W. Porter, after the author

sent the path of the center of the mirror. Both of these strokes differ from the 'cross-and-back stroke, in that they bring practically no abrasion to bear on the edge of the mirror and the center of the tool, almost the whole weight of the upper disk being balanced on or near the edge of the lower. In the more conventional 'cross-and-back stroke there is considerable wear all over both disks and the concavity is gained only because there is more wear —perhaps 50 or 75 percent more—in the one area than in the other. This wastes glass, abrasive and elbow grease. However in the various off-center strokes much abrasive is lost by being pushed off the disk; also these strokes are not as comfortable to perform as the 'cross-and-back stroke.

A third variation is the epicycloid, as in *c*, where the curve, rather idealized, represents the path of the center of the mirror. This has its uses; sometimes for evening up a curve that has become irregular (sometimes, too, if care is not taken, it will make a regular curve irregular); sometimes just to vary the monotony of grinding. Stroke *c* will act about the same, as far as distribution of wear is concerned, as the 'cross-and-back stroke.

All of these strokes are capable of playing bad tricks, but if the worker who has already made a mirror by the 'cross-and-back stroke will experiment with them, or with combinations of them or other modifications, he doubtless will acquire more general skill than he previously had. In different hands they exhibit different idiosyncrasies; hence the individual worker may experiment for himself. In general, they will tend to deepen the center unduly and should be used with circumspection when employed in the fine grinding stages—if used then at all.

The Correct Level for Grinding and Polishing is exactly where you find it most comfortable. Most beginners work too low and their spinal column acquires a case of the washtub bends. J. W. Fecker states that in his shops, work on the lap is done at such a height that the forearms are horizontal.

Why Disks Grind Concave is explained in Part I, Ch. I. The abrasion is increased when the upper disk overhangs, due to increased pressure on a given area. A more common explanation is that the center of the upper disk is under abrasion all of the time, while the edges are under abrasion only a part of the time. This at first seems quite logical, but if it is the true explanation, why is the center of the lower disk not also abraded more than the edge?

Who Discovered the Method of Concaving a Glass Disk? The common method in which two disks of equal diameter are ground together was discovered by Professor Elihu Thomson and described by him in a communica-

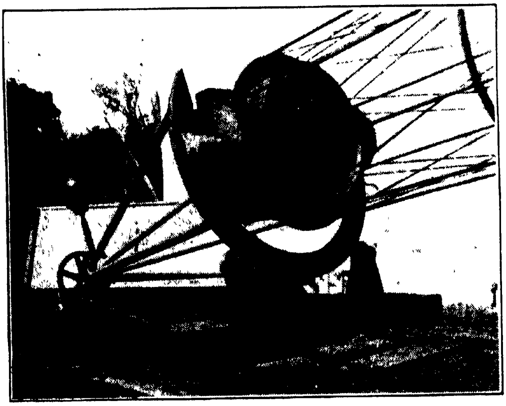
A 21-inch reflector with split equatorial ring type mounting, made by George H. Hamilton of Jamaica, B.W.I. and described in The Scientific American, May 1929, pages 442–443. This telescope weighs 1600 pounds. The mirror was made by hand, with a 12-inch tool. Sub-diameter tools require expert skill.

tion to the *Journal of the Franklin Institute*, 1878, pages 117–121, entitled "A New Method of Grinding Glass Specula." The same paper was reprinted in the *Scientific American Supplement*, Sept. 14, 1878. However, there is a question whether the same method was not previously discovered and used by Short, more than a century previous. Even if so, it would make no difference in this case, because, as Ellison has stated in a letter, "If Short, in 1750, found that he could make specula quicker and better with an equal disk of the same metal as a tool, he would certainly not tell the world, but would keep the secret for his own profit." By a sacred tradition in science he who makes a discovery and thus withholds it for his own use receives no credit for it; not even if he bobs up later, when someone else independently makes the same discovery and unselfishly publishes it, and attempts then to

claim credit for it. Short was excessively secretive (see Bell, "The Telescope," page 27).

Previous to this discovery the accepted method was to form the tool to the desired curve first.

Ellison states that "Wassell had the disk-on-disk method a good many years before 1878." He refers to some articles by Francis, describing it, in Volumes 7 and 8 of *Amateur Work,* which antedate the Thomson articles cited above. He believes Professor Thomson discovered the method independently.



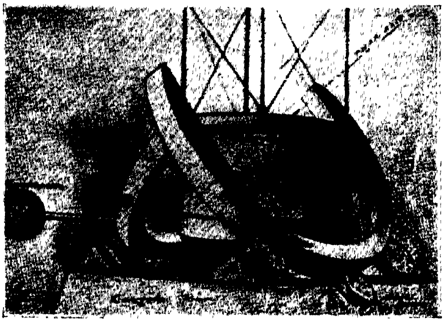
Detail of the mounting (Porter ring type) of the Hamilton telescope.

Keeping Track of the Radius of Curvature While Grinding may be done as described by James C. Critchett. The mirror is centered on the tool and a sight is taken along its top before grinding is begun. Mark the point on some convenient wall or vertical fixture at a distance from the center of the tool equal to the radius of curvature desired. Next, measure and mark a distance below this reference mark equal to one half the diameter of the mirror. Whenever it is desired to measure the amount of concavity of the mirror as grinding progresses, the mirror is slid toward the wall one half its diameter, so that its edge rests on the center of the tool. It is then weighted so that it will not tip off, and a sight is again taken along its top. When the line of sight reaches the lower mark the desired radius has been reached. If nothing on which to make the marks happens to be at the right distance from the tool one may choose some more distant surface and increase the vertical distance-to-go in the same proportion. Further to refine this method, Critchett made a simple sighting telescope consisting of an inch lens of a few inches focal length and a smaller lens of shorter focus, mounted in notches on the edge of a straight-edge. He fastened a needle with its point at the

focus of the eyepiece and with this, which is simply a small telescope without a tube, be obtained still more accurate readings. With a little planning beforehand the same lenses may later be used as a finder for the telescope. See note on "*Finders.*"

Very Exactly Finding the Radius of Curvature when grinding may be done by giving the surface a five or ten minute pseudo-polish with an old lap and rouge, and then measuring by the knife-edge test. The lap need not make good contact. This method also facilitates greatly the study of pits. It works poorly at the 120 stage but better following the 280 stage.

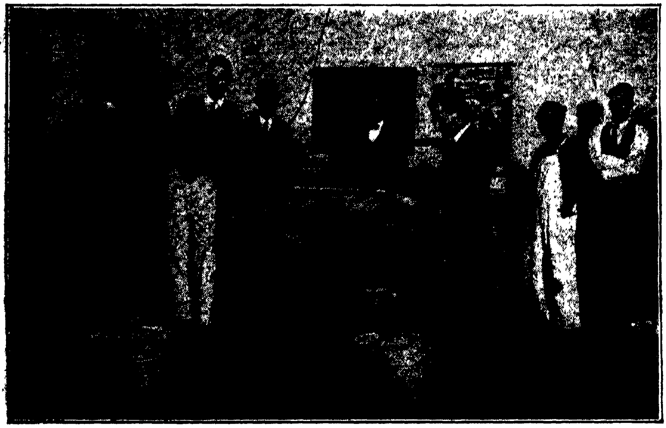
Designations for Carbo Grain Sizes are mainly nominal and in most cases do not express the rate of fall through water, as formerly. The following statement by Henry R. Power of The Carborundum Company explains them: "Abrasive grain sizes No. 220 and coarser are defined clearly in the Simplified Practice Recommendation R118–30 of the Department of Commerce. Grit Numbers 240, 280, 320 and 400, which are the powder sizes, are defined by standard samples of the Abrasive Paper and Cloth Association. These



The split ring equatorial mounting (see Part I, Figure 26) was the invention of Russell W. Porter and was originally described in Popular Astronomy, May 1918, page 147 (reprinted in Scientific American Supplement, August 3, 1918, page 77) from which this drawing, made by the inventor at the time mentioned, is reproduced. See U. S. Patent No. 1,468,973; Sept. 25, 1923.

may be placed in a sedimentation tube containing a fluid of known viscosity, and the amount collected in a unit time measured. The size in microns is plotted against the percentage, giving a curve which should be matched in the commercial preparation of these powders. The symbols are nominal. The symbols '1 min.', '15 min.', '60 min.', etc., are now obsolete with us, though I presume they once referred to the time required to settle the powder in water. The symbols F, 2F, 3F and 4F are used for powders less accurately graded than the numerical gradings 240, etc. above referred to. These symbols are nominal."

Crushed Steel and Pyrex are said by Napoleon Carreau, optician, of Wichita, Kansas, to be a logical combination. Pyrex is about twice as hard as plate glass. "I can do in one day with Crushed Steel what I cannot do with Carborundum in four days, when grinding Pyrex," Mr. Carreau writes. "Crushed Steel can be used a great many times over without apparent loss in grinding quality. It scores the grinding tool and wears it out very fast, but saves time. When one throws a teaspoonful of Crushed Steel between the grinding tool and the Pyrex, one hears a sharp noise that keeps on until the



Typical amateur activities. Members of the Amateur Telescope Makers of Los Angeles in their shop. In the background is the machine shown in Part V, Figure 4. Also note pedestals of pipe cast into washtubs filled with concrete. This provides a pedestal heavy enough to "stay put," yet capable of being rolled about and moved when desirable.

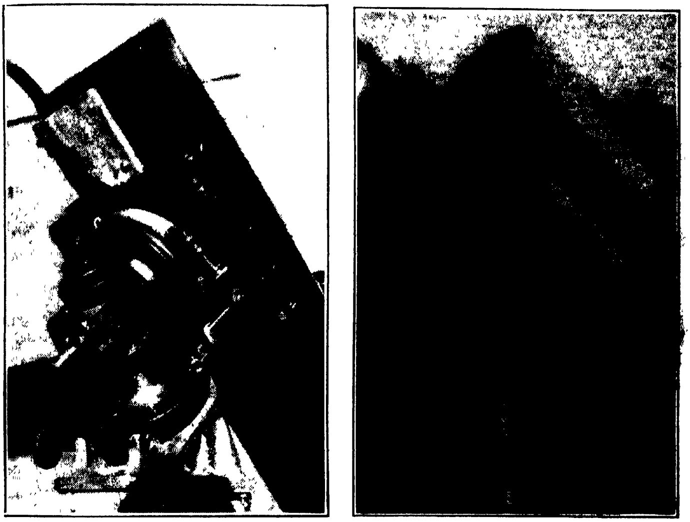
steel is all thrown out. The same Crushed Steel may be thrown back between the tool and Pyrex and the noise is again about the same as it was before. Those who do not notice very much difference between the grinding qualities of the two abrasives on Pyrex may not be using enough pressure."

For the benefit of beginners it may be pointed out that, while Crushed Steel is a gross abrasive, the gain will scarcely pay when making small mirrors, while the coarse grains in relatively inexperienced hands may leave pits which will cause much trouble later. When working on large disks, or on smaller hard ones such as Pyrex, this material will probably effect a saving in time, as it will hog out the bulk of the glass in rapid fashion.

Bad Central Contact in Final Grinding, with the outer zone refusing to wear down and allow the inner zones to make spherical contact, may be due to the use of too thin and watery a paste of Carbo. Capillary attraction

draws the abrasive off the outside zone and down over the edge, and the central zones receive more abrasion than the outer zones. When this situation arises, a rather stiff paste of Carbo will usually deal with it and permit the two disks to be brought to concentricity. To this, Porter adds the suggestion that side pressure be applied to the edge of the disk (as in Part I, Figure 16).

Searching for Tiniest Pits is largely a matter of the conscience. Pits which can be allowed entirely to escape an ordinary examination, even with a lens, may be detected if the lighting is correctly arranged. The disk should be placed within one or two feet of a strong light (*e.g.*, a 40- or 60-watt bulb), and tilted so that the reflection of the bulb appears on it. With a



The Pasadena version of the Springfield mounting as made up, left, by H. O. Bergstrom of North Platte, Neb., from combination of pipe fittings and solid metal and, right, by Arthur H. Jones of Chattanooga, Tenn. In the latter 3-inch pipe fittings are used throughout · a 45° L, close nipple, a 3"×2"×3" T, a plug bored out for eyepiece, and a 3"×2½" bushing at the tube.

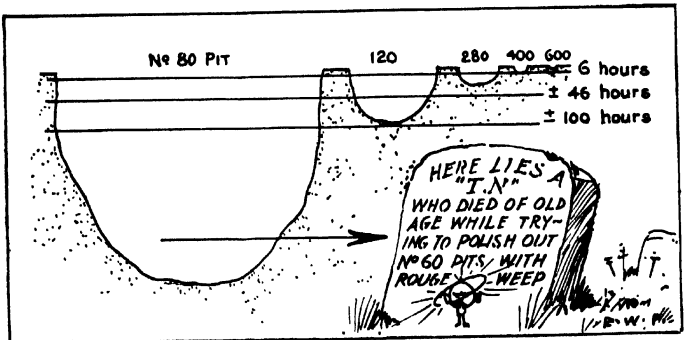
lens the areas at either edge of this reflection are then studied critically. Lighting at such an angle will reveal tiny pits and defects through a common reading glass which will get by when a strong lens is used with incorrect lighting. Another way is by transmitted light—through the disk from behind.

Futility of Attacking Big Pits with Rouge: "Although I have polished, to date, something like 30 hours, there seems to be no diminution of pits.

I took what I thought to be the utmost care in fine grinding, and although the rouge polishing went quickly enough, getting rid of the remaining pits is the stumbling block I have encountered. I have tried several new laps, thinking that might be the source of the trouble, but nothing seems to help."

So writes one worker. Here is a note from another: "There seems to be something rotten in Denmark, for I have been polishing my mirror for 46 hours. It looks perfect to the naked eye, but a lens shows up many pits."

These letters are typical of many. There *was* "something rotten in Denmark." Quite a few beginners (and some others) get into this fix. Pits—



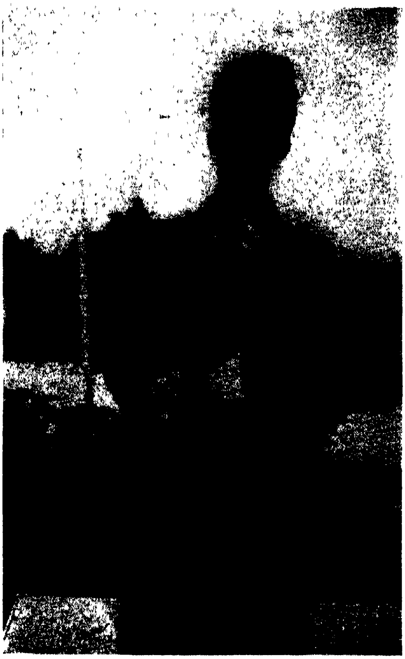
Drawing by Russell W. Porter, after the author

even large ones—are real adepts at the art of camouflage, often "hiding out" despite inspection with a lens.

We may look at it thus: Each size of abrasive in the series used has its characteristic depth of pit, this depth being roughly proportional to the size of the individual grains of abrasive. Let us assume that we have a surface on which there is a mixed collection of pits due to all of the sizes of abrasive (see sketch).

First, the flat level areas between the pits will come to a polish within a few minutes, and if a way could be found to grind a glass and leave no pits of any kind, the polishing job would be complete then and there. Or, if we had a series of abrasives logically filling in the big gap between the smallest available size of Carbo, and the far tinier particles of rouge (about 1/25,000-inch), we doubtless could shorten the polishing operation quite considerably. But we have no such ideal series. The finest grade of Carborundum is of the order of 100 times the size of the particles of rouge. Therefore we must dedicate some six or more hours work with rouge to planing the glass down to the level of the bottom of the pits even for those due to the finest abrasive used in grinding, not to speak of the coarser ones. The latter would not, however, be there at all if the medium-sized abrasives had been used *long enough at the right time.*

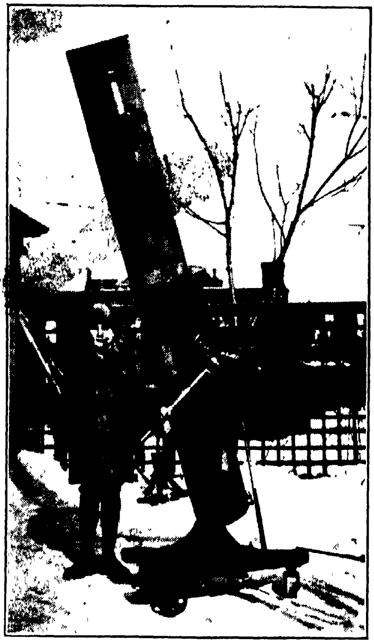
Now suppose we discover that we have some No. 400 pits but no larger ones. With rouge we could also wipe these out—probably by about twice as much work as required normally for No. 600 pits. But suppose we had pits inherited from much coarser abrasives, No. 80 or 120. The diagram shows how brave a man would have to be to expect to abolish these by polishing with the comparatively slow cutting abrasive called rouge. This is what the workers whose plaints are quoted above were doubtless trying to do.



Alan R. Kirkham and a 16-inch cemented disk made of two disks of 1-inch plate glass separated by 20 blocks of glass, 1 at the center, 7 in the inner ring and 12 in the outer ring. This type of built-up disk was suggested by the late Henry H. Mason of Florida and is called Mason's ventilated disk.

The moral is obvious: It is more costly to let go the clearing up of pits due to *coarse* grinding than those due to fine grinding. All the subsequent fine grinding will probably leave them scarcely at all reduced in depth. And at that—and worse yet, too—for a long period of hours most of them will be

playing hide and seek among smaller sizes, making the worker think they have gone. But they will turn up, like the cat that came back, to plague him and make faces at him after hours of polishing removes all the pits due to finer abrasives, thus causing the mirror actually to look *worse and worse,* after more hours of polishing.

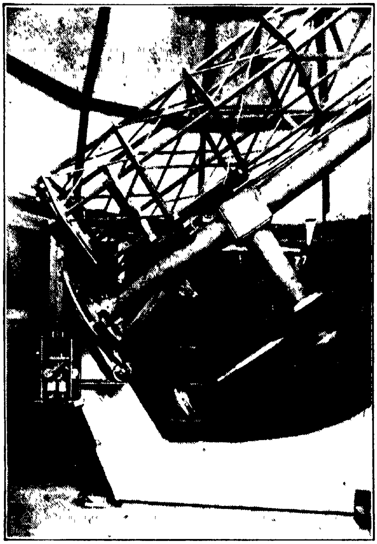


A portable 12-inch reflector made by H. L. Rogers of Toronto.

Each size of abrasive requires at least an hour. An extra half hour on the second, third, and fourth sizes may prove to be a paying investment, even if the surface does not look as if this were necessary. Remember Benjamin Franklin's story of the man who shirked the pits in his ax: "The man who, in buying an ax of a smith, my neighbor, desired to have the whole of its surface as bright as the edge. The smith consented to grind it bright for him, if he would turn the wheel; he turned, while the smith pressed the broad face of the ax hard and heavily upon the stone, which made the turning of it very fatiguing. The man came every now and then from the wheel to

see how the work went on; at length would take the ax as it was, without further grinding. 'No,' said the smith, 'turn on, turn on, we shall have it bright by and by; as yet it is only speckled.' 'Yes,' said the man, 'but I think I like a speckled ax best.'"

Get a Sphere before Beginning to Polish: When a worker states, as many have, that after polishing his mirror he has a difference of 3 or 4 inches between the radii of different zones, it is unlikely that he has derived so gross a discrepancy as this merely from polishing, no matter how poor a lap he has used. Doubtless it is an earlier inheritance from grinding. When the pencil test indicates in the finest stage of grinding that the mirror and tool are out of sphericity (contact) by more than the thickness of a pencil mark at any point it is almost futile to go ahead with polishing in the



A 15-inch reflector made by E. H. Morse of Altadena, California.

vague hope that, somehow, something will "happen" to straighten it out later on. It will sooner or later become necessary to return to fine grinding because, short of almost a lifetime of hard work, the thickness of glass involved cannot be removed with so fine an abrasive as rouge. If the pencil mark is rubbed off in some places along its length, but only touched in others, it is safe to begin polishing, for rouge will handle that discrepancy, since it is of the order of size of 1/5,000 of an inch—about the amount normally shaved

off the glass by the rouge during the polishing operation. Sometimes it rubs everywhere except at the edge. This, if permitted to remain, will inevitably mean a grossly turned-down edge later on.

This note partly repeats statements made in other notes. It might, however, be inserted **at ten different places and in capital letters,** to the advantage of the beginner, who very often falls heir to trouble in polishing or

A 16-inch reflector made by A. V. Goddard of Portland, Oregon.

figuring perhaps because he does not sense these realities until he has come hard up against them. This is one important matter which Ellison omits to emphasize.

Laps and Lap Making: Next to silvering, no part of the telescope making art has proved so difficult for the beginner as making a lap of pitch. Some have reported failure after five, ten, or as many as fifteen attempts. It is suspected that the majority of laps made in such cases would have performed well if they had been saved and used, but the available instructions have been too sketchy to enable the beginner, who may never have even seen a lap, to judge whether the one he has made is actually good, bad or in-

different. The common pitch lap may start in life like many youths—an untidy, unlicked object of pity, yet may come around in good shape after all. Or it may really require remaking.

At the risk, therefore, of insulting the intelligence and gumption of those who are gifted with more natural aptitude than the rest of us, a rather detailed outline of one way—there are many—of making a pitch lap will be presented.

Place the tool in a pail, blocking it up off the bottom with some metallic object which is fairly open, so that the glass will heat evenly—a heavy wire suitably bent will serve well. On top of it, place a second spacer. On this place the mirror. Unless thus exposed to the water nearly all over their surface, the disks when heated may expand unevenly and crack, rendering them worthless. Fill the pail with cold water just barely above the level of the top of the upper disk and heat its contents slowly. It should be given

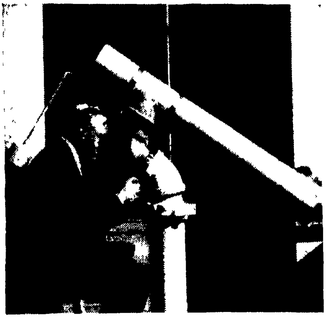
A 12-inch reflector with fork mounting and synchronous induction motor drive, made by Ralph C. Patton of Providence, R. I.

as much as 20 minutes to reach about 110 degrees F. This corresponds to the temperature of hot bath water. Do not hurry the heating or you may crack the disks. If disks at higher temperature, or even at 110°, are exposed to icy air or drops of cold water they may crack.

Place some pitch in an old can and heat it rather slowly—if heated rapidly the fumes may take fire. Pitch does not explode, but it burns rather vigorously and it is, therefore, well to have on hand an old coat to throw over it in case of eventualities. If the heating is well managed, the disks and

the pitch will reach their respective required temperatures together. Do not let the pitch boil, as this favors the development of bubbles in it. You will have some bubbles anyway, but there is no point in getting more of them than is necessary.

While the disks and pitch are heating, assemble within reach a dry towel or cloth, a bit of absorbent cotton dampened but not soppy with turpentine, and a strip of heavy paper a few inches longer than the circumference of the tool and about 5/16 inch wider than its thickness at the edge. It should



At left, a solid rugged mounting, made of 6-inch pipe fittings. These cost $8.50 and the maker, Byron L. Graves of Los Angeles, states that this small sum proved to be a sound investment in steadiness. Vibrations which cannot even be detected when looking at a telescope become very troublesome when looking through one. At right: An eight-inch reflector made by Joseph Kuhn, Wisconsin Rapids, Wisc. This picture, like the other one, is inserted mainly to emphasize more strongly the desirability of providing a really rigid mounting, judged not by ordinary standards of rigidity but by telescope standards. Mountings made of small pipe fittings are in the "India rubber class." They shimmy. While full six-inch parts such as those shown above need not be employed unless they are readily available, it is better to err on that side of about 3 inches than the shaky side. When pedestals are cast into a concrete base the concrete should go lower than the frost line and be tapered to smaller size at the top, so that the expanding frozen earth cannot heave the telescope out of adjustment.

have perfectly straight edges. Provide some heavy twine or several good strong rubber bands and a little rouge mixed with water, or else some very soapy water, preferably lukewarm since even a drop of cold water may crack a warm disk.

Find a level place to rest the tool later on when pouring the pitch. It is well to use a level if your eye is not pretty good.

Remove the warmed mirror from the water and set it aside. Remove the tool and replace the mirror in the warm water, but do not permit it to go on becoming warmer. Dry the tool and be sure to dry both hands, for drops will otherwise fall on the glass and prevent good adhesion of the pitch. Take plenty of time—there is no rush. Many laps are botched because of hurrying the job.

Wrap the strip of paper around the tool, keeping its lower edge level with the bottom of the disk, and tie it on with string or snap the rubber bands around it. Another way to attach its ends is with a dab of hot pitch. The joint need not be very tight, as even melted pitch is thick. Make sure that the paper extends a uniform distance above the glass—say, within 1/16 inch of the 5/16-inch thickness previously suggested. Moisten the tool with the turpentined cotton.

Pour the pitch on the tool, distributing it reasonably well. If it is not finally level no very particular harm will result, but a wedge-shaped lap will always be bothersome to work with. Melted pitch will shift some and partly level itself but not as water will, so it should be fairly well distributed.

Now sit down and have a smoke and cool off.

After a few minutes—perhaps five or ten or even more—the pitch, judged by a touch of a wetted finger tip (Ecclesiasticus XIII, 1), will be firm enough to stand up without the paper. Strip off the paper, or as much of

Armagh Observatory, at Armagh, Northern Ireland, of which the Rev. Ellison is director. On the left is the fine old stone residence, built about 1790, with a dome on top which houses an ancient unused telescope. The low wing on the right is Ellison's library and study. Next to the right, connecting through a passageway, is a square-roofed transit house, and beyond is a high old stone tower with dome which now contains a 6-inch refractor made by Ellison. At the extreme right is the low roof of Ellison's compact stone-walled optical shop. The two modern telescopes he uses, a 10-inch refractor and an 18-inch reflector, are in domes at ground level but these do not show, being behind the reader's point of view. The observatory is romantically situated on a low knoll and is surrounded by a grove of fine old boxwood trees.

it as you can easily get off, smear rouge and water or soapy water liberally on the lap and mirror so that the latter will not stick, and let the mirror lightly down. Do not slap it down, for this causes bubble-holes in the lap. It will make bad contact at first, but you still have 15 or 20 minutes in which to make it conform reasonably well, and the lap will not really harden for another hour or two.

At first supporting a part of the weight of the mirror, in order to prevent

it from pressing in too deeply wherever it rests off-center and thus leaving a ridge in the pitch at its edge which will be hard to manage, move it an inch or less in different directions. This will tend to make the pitch conform. As it cools this may be done with more pressure but only for a brief time in any one exact position. If possible, do not at any time short of an

An 8½-inch telescope built in 1930 by Rev. Ellison, for José Fernandez of Argentina.

hour or two lift the mirror entirely off, as its return to the soft lap may trap air under it and introduce unnecessary bubbles. If you must lift it off, replace it by sliding it on from the side, lightening its weight at the same time, so that its edge will not plow up a ridge.

During all this conforming process some pitch will continue to creep over the edge of the tool. This will do no harm.

Remain near by for an hour or so longer, occasionally moving the mirror. Even after that there will still be time to repair any big bubble holes you may have seen through the glass. Either pour melted pitch into these with a spoon, never quite filling them since an excess will be bothersome, or stuff

into them little chunks of pitch softened in the warm hand, replacing the mirror and working them down level. They will not look pretty, but never mind. The pitch may not appear to give promise of joining, on account of the rouge or water already in these holes, but it will stay there quite well enough to do business. Remember that one way to make a lap is actually to dig holes in it, here and there, instead of channeling it. Hence holes, in themselves, cannot ruin it—unless the lap is practically *all* hole. It is believed that hundreds, if not thousands, of newly made laps have been needlessly sacrificed by beginners because they resembled a piece of Swiss cheese. Examine the grouping of the holes *with regard to zones,* not with regard to sectors, and size up the situation. For example, holes fairly evenly

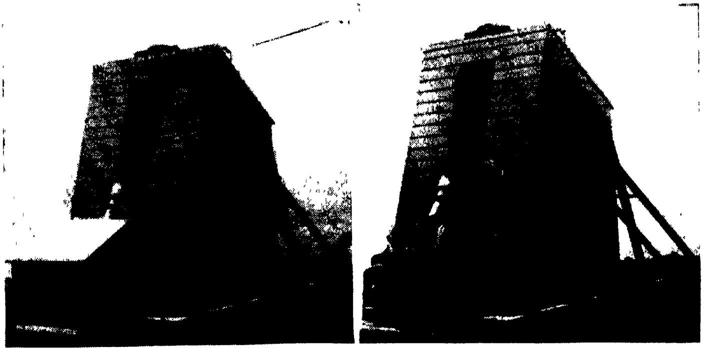
The Rev Wm. F. A. Ellison.

distributed throughout all zones, even if all on one side of the lap, will probably do no harm, since the mirror is to be rotated during polishing and this will prevent any sectorial effects on the mirror. Judge all this by a blow of the eye and try to plug up the larger holes where needed or, on a pinch, even make compensatory holes in certain zones, which should do no harm. It is true, the holes will reduce the total area of abrading surface, but the pressure per unit area will be increased correspondingly. No matter how inexpertly you perform this preliminary balancing of non-contact spots in zonal areas, the results will show up very soon under the knife-edge test and, long, long before it matters much, you will know through that test

where to alter the lap further. Softened pitch can be worked into holes at any future time. So it is not yet time to condemn the ugly looking lap.

This wet-nursing job on an infant lap will probably demand your intermittent attention for two hours the first time you make one. Do not, even then, leave the mirror on the lap and go off fishing, as it is still partly warm (feel of under side of glass tool). Warm pitch crawls—faster too, when you are not looking—and it may in some way bring about disaster; for example, depositing mirror and all on the floor.

In addition to large cheeseholes myriads of little tiny holes often appear on a lap. These are due to bubbles in the pitch. They will not do any particular harm, but enough of them in one zone may cause unequal abrasion. As they are too small to plug up with pitch they may be compensated by making a few shallow holes elsewhere, and they will gradually fill in under pressure as the polishing proceeds. Do not be in too much of a hurry to



An enclosed observatory and telescope designed and constructed by John H. Hindle. Left: With the flat and diagonal covered. Right: Uncovered and ready for use.

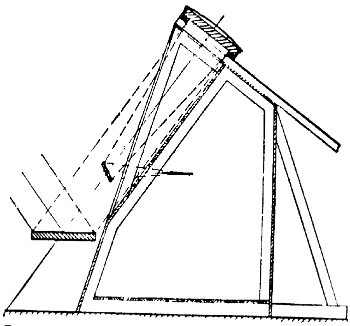
compensate them, however, but first polish twenty minutes, or even more, and then try the knife-edge test. Regardless of the appearances of the lap, that test is what will tell what, if anything, is wrong with it, and where. If the lap is polishing evenly, leave it alone, no matter how bad it looks.

Of course, a nice smooth lap without any holes is altogether desirable, and after a little experience the worker will learn to make such a lap.

If the lap turns out to be rather thick, more than one half inch, no particular harm will result unless the working place is hot, above about 80°, when it may give considerable trouble by slumping. It will also require more subsequent trimming up. If thinner than one eighth inch it may be slow in the matter of establishing contact, but it possibly will serve. Ellison recommends one eighth inch, which is thinner than most other workers use. A quarter inch or 5/16 inch is a fair average. It is impracticable to specify

too closely, because many of the factors—local conditions, temperatures, quality and hardness of pitch, personal working idiosyncrasies of the worker, etc.—vary. For the same reason there is little use in attempting to work out a standard of hardness of pitch for the amateur. Suffice it to say that laps having quite a wide variety of characteristics have performed well. It is best to aim at the norm but, within limits, variations need not spell disaster.

An alternative way to make a lap is not to warm the two disks at all. This is far less trouble and consumes comparatively little time—if you can make a good lap in that manner. After trying it, many may vote to warm the disks. The hot pitch strikes the cold glass and hardens almost immediately, allowing the inexperienced worker little time to nurse the lap into shape.



Drawing by John H. Hindle

Diagram of the optical train of the Hindle enclosed observatory. The flat of the coelostat has a diameter of 25½ inches. The primary disk is 25½ inches in diameter but only 20 inches are excavated, so that the telescope actually has a 20-inch paraboloidal primary. Its focal length is 96 inches. The tip of the cone is turned into the house by means of a diagonal. The only moving part is the coelostat. The extension below the diagonal contains a flat for a finder. The building faces south and the latitude largely determines its slope. It is very rigidly braced.

The methods described above state only one way of making a lap. There is no law or set rule about the job. However, this way has worked well many times. After you have made a few laps you may find ways to short-circuit much of the detail, do it all in a few minutes and no longer make a botch lap requiring "pointing up." An old hand may make a lap and be working on it, within 30 minutes.

The tool and lap now being entirely cold after perhaps a couple of hours (next day is better, if convenient), channeling is in order. The overhanging pitch at the edge may be trimmed off, because it may cause a turned-down edge. It is better on the same account to reduce the diameter of the lap to a quarter or eighth inch less than that of the mirror by champ-

fering the pitch at an angle. This may cause turned-up edge, but the latter is easier to deal with than the former. Use a sharp knife and shave with little short strokes, instead of plowing boldly ahead before you have learned how peculiarly pitch behaves. This will tend to prevent taking big chips out of the face of the lap.

For Everest's test and scale of hardness, press one pound with thumbnail (practice on scales beforehand). If a ¼-inch dent is made in 2 seconds the lap is very soft; if in 10 seconds it is medium (normal); if in 20 seconds it is hard, and if in 40 seconds very hard. Judge hardness only after several hours of cooling: regarding this see opposite page.

Four purposes for the channels in laps are: (1) To distribute the rouge—local pick-up sources. (2) To prevent suction. This will be demonstrated the minute they are allowed to close in—the mirror behavior then becomes cantankerous. (3) To facilitate perfect contact, by providing the pitch, under pressure, with an escape; otherwise it must travel all the way out to the edge of the lap. Hence the deeper the channels (taller the pitch columns) the quicker the response, on pressing, and so it is generally well to cut the channels clear to the tool. Beware of chipping the tool; the chips may scratch the mirror. (4) Perhaps the most important purpose is "to overcome the lubricating effect of the fluid film between an ungrooved lap and the work. When two surfaces of nearly the same radius are brought together in a fluid medium, and relative motion occurs, unless the surfaces are held rigidly parallel a pressure film of the fluid is formed between them, which tends to force the surfaces apart. The film will be wedge-shaped and thickest where the lubricant enters the film. For example, in a well-designed oil lubricated bearing, the minimum film thickness may be of the order of .001 inches, increasing to a maximum of perhaps .002 inches. Should we divide our bearing surface into facets by cutting grooves the lubricant will have open paths of escape when the load is applied. This destroys the film and permits the surfaces to come into contact."

With a straight-edge and everything wet, to minimize sticking, draw a pair of pencil marks for each channel, starting with the one just off-center, as explained by Porter and Ellison. Then cut them out. Do not bear heavily on the straight-edge, as this will indent the lap; and do not bear heavily on the knife, as this will be likely to press out large chips of pitch where it is not desired to remove them. Little short strokes, especially before the "feel" or knack of cutting pitch has been learned, may prove best. Do not try to cut far down at one cut; the better method is to keep enlarging the cut by increments, working on one side of the channel, then on the other, etc. Slope the sides of the channels about 60° more or less, as the pitch will not then chip so readily from the sides of the facets.

It will probably pay to practice a bit by cutting some pitch poured on a board, and thus learn something about pitch, which is rather "cussèd."

All this is a mussy job. Clean up with rags and turpentine.

In case you have to boil the pitch because it is too soft, a short boiling will have little effect. A lot of boiling is required to alter its hardness more than a little. Ellison tests the pitch from time to time while thus boiling

it, by dropping a sample into cold water to cool. If this is done it should be given "several minutes" (Ritchey) to cool, else the apparent new hardness may be deceptive. The water should be "at the temperature of the polishing room" (Ritchey). There seems to be a sort of time lag in the hardening of pitch—perhaps this is an illusion of some kind—whereby it often seems to have cooled to the temperature of its surroundings, yet will become harder some hours or a day afterward. The probable answer is that it has not actually cooled to the temperature of its surroundings when one thinks it has. When Ritchey makes a lap he allows the pitch to cool "for six or eight hours."

Mr. Hindle at the eyepiece of the enclosed observatory telescope, which is fixed, horizontal and comfortable to look through.

Modifications of the Plain Pitch Lap.—These are numerous. There are almost as many as there are lap makers. Each worker, after following the rules of Hoyle in making a lap of two, usually introduces his own variations. If the variations are good this expression of individual inventiveness is good, but where variations are frowned on it may be just possible that the variation is intrinsically bad, and not that the frowner is stuck in a rut of orthodoxy.

John H. Hindle's pet lap is made of asphalt (pure Trinidad bitumen) thinned down by turpentine or one of its substitutes until it is quite soft. After the lap has been channeled he brushes on the surface one even, thin coat of beeswax, using a warmed brush of good width. The coat of beeswax should be scarcely any thicker than a sheet of paper. Ritchey also uses beeswax. In the famous treatise "On The Modern Reflecting Telescope,"

etc., which is now out of print and scarcer than pigs in Palestine, Ritchey describes the manner of application: He strains the beeswax, then brushes it on by a single stroke of the brush. "The wax should be very hot," he says, "otherwise the layer will be too thick." His brush is made "by tying several thicknesses of cheese cloth around the end of a thin blade of wood 1¼ inches wide." Incidentally, Ritchey makes his own pitch by melting rosin, and after removing it from the stove, as turpentine is inflammable, adding turpentine to the extent of about $\frac{1}{25}$ of the weight of the rosin, depending on the amount of turpentine already in the lap, and stirring thoroughly. A very little turpentine will effect a big change in the hardness of the mixture.

Others have similarly painted on the plain pitch lap a coating of paraffine wax, grafting wax, floor wax and almost every conceivable variety of wax except possibly ear wax. The intended purpose of using wax is to give the glass a smoother polish, which some claim it does, and to reduce risk of scratching. Note that Ellison mixes the beeswax with the pitch, largely for another purpose (to render it more tractable), while these other workers merely paint it on the surface at the top.

Some have also painted wax or pitch in a thin layer directly on the glass tool. This will polish the mirror and may enable the worker to figure it if he is lucky, but the adaptive qualities of the thick pitch lap are then entirely abandoned, for wax will not flow as pitch will. In fact, a thin layer of pitch will flow relatively little. With wax on pitch the valuable qualities of both materials are exploited.

The HCF Lap has been widely used since Part IV of the present work was published in 1928. Many workers swear by it; some swear at it. When the correct conditions are obtained it gives an excellent polish, as there is much less tendency to cause zones than there is with a channeled pitch lap, probably because the pattern of the facets is finer. The more enthusiastic early claims for much more rapid polishing than pitch affords have not been altogether borne out. Russell W. Porter reported in *Scientific American*, July, 1932, page 53, that "comparison tests have been made here (*i.e.*, at the optical shops of the California Institute of Technology, Pasadena, California) on a number of lenses, half of them polished with a cast-iron tool covered with the comb foundation and half with the ordinary tool of pitch facets painted with beeswax. Aside from the differences in the tools these lenses received identical treatment on the machine." The results were that the length of time required to produce a complete polish was about 10 hours. The rapidity of polishing with the two tools was about the same. These tests were made on a group of 7¼-inch lenses. At first the HCF lap was made of three layers of HCF on the cast-iron tool, but the polish came up unevenly. Three more layers of HCF were added, and the six then gave a sufficient cushioning effect to permit good contact to be secured after cold pressing. This is an unusual way to use HCF—a sort of glorified club sandwich of HCF sheets.

The tests mentioned above are really tests of beeswax in the form of

HCF, against beeswax painted on a pitch lap. But the time consumed was nearly as long as that required in plain polishing. Others have claimed faster results when polishing on HCF than on plain pitch.

HCF may be used in several ways, the one in Part IV having been recommended by Everest because, after experiments with many kinds of HCF laps, he believes that one superior. Some of these ways are:

(1) HCF applied direct to the tool. (*a*) Rub beeswax (a scrap of HCF) over the glass, to charge it, lay on a piece of HCF, add mirror and cut around it, rub soap on its face and go to work. The HCF will not skid sidewise but may be lifted off at any time. (*b*) Another way, also cleanly to make, is: Heat tool to temperature of a hot potato, lay a sheet of HCF on top, then mirror, and add 3 to 5 pounds weight. Let cool. Trim HCF and go to work. If potato was not too hot or too cold, HCF will not be harmed, yet will adhere strongly and permanently.—B. R. McCrary's lap. D. Everett Taylor attaches HCF to the tool by means of what he calls "pitch paint"—pitch cut in acetone.

(2) HCF cold pressed deeply into a pitch lap of ordinary thickness and left there. (*a*) On unchanneled pitch. With this lap good contact will be good luck, since the pitch must crawl a long way sidewise to give contact on top. Note: If the pitch and under side of HCF are heavily soaped beforehand, the HCF may be stripped off later, if desired; or channels may be cut through both, leaving HCF on facets. (*b*) On channeled pitch. The HCF bridges the channels. Fine contact until channels flow full.

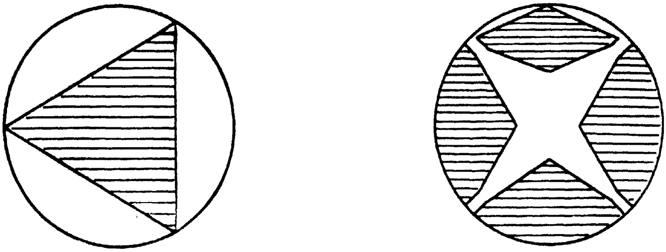
(3) Whole HCF pattern transferred to a pitch lap. Soap pitch and under side of HCF, cold press HCF in deeply. Strip off. In channeling, follow the pattern on the pitch, entirely removing 1 in 7 or 8 rows. Begin one row off center. Cross channels will be diagonal, following the HCF pattern but beginning two rows off center. A third diagonal set of channels is hardly necessary, hence facets will be diamond-shaped. This lap will drag hard and even screech out loud. Combines qualities of pitch on top parts and the HCF "wedge" at forward edges of depressions. Is a pretty lap to look at but is sometimes tricky. Produces too much heat for final fine work.

All of these laps, if used at all, will bear close watching.

Joining HCF sheets edge to edge is possible though difficult. They come in two widths, 8 inches and 10⅛ inches, and if a larger mirror is to be polished two sheets must be joined. If they are merely butted without being welded the pitch will gradually work up between their edges, spread out near by and, because of the added abrasion, cause a depressed zone to form. Two sheets of HCF are therefore slightly overlapped and the two are cut at one stroke (to insure an accurate fit). They are then pressed against the respective sides of a piece of warm metal, the metal is quickly withdrawn and the HCF sheets are instantly slid together before cooling. To do this skilfully one must almost be a prestidigitator but it can be done, and neatly, too, after some practice.

Special HCF laps for figuring are described as follows by James C. Critchett: "While experimenting with superimposed pieces of HCF, I hit upon the following principle, which has so far worked out nicely in securing

spherical surfaces, preliminary to parabolizing: When a polygon of HCF is placed upon an HCF-covered tool, so that the edges of the polygon form chords of the tool circle, the abrasion delivered by the polygon is eased out to the edge of the mirror without leaving narrow zones or any zones, if ordinary care is taken. Thus a high center can be rapidly and evenly worked down with a triangular secondary lap, as shown in the first sketch. Following this, if so justified by the resulting figure, the mirror is worked with a square or rectangular piece of HCF of which the edges are chords of the tool. Low edges can be nicely brought up with pentagons or hexagons, etc. A partial chord will have the same abrasion-distribution effect, more locally applied. In case of a low center one can make a secondary lap by cutting a circle of HCF to fit the top of the tool, quartering it and trimming it as



Drawings by Russell W. Porter, after James C. Critchett

shown in the second sketch, thus getting the chord action. By cutting segments from the edge zone one can also use these pieces for bringing up a low edge, thus securing hyperboloid rectifiers. The second sketch is thus a modification of Ellison's star lap. The ends of the pieces should be cut off enough to allow some shifting between edge and center of the tool."

The Paper Polishing Lap turns up, every now and then, as a substitute for the pitch lap. Some defend it stoutly but the majority of fine workers condemn it roundly. What Ellison thinks of it is reprinted from *English Mechanics*, Feb. 1, 1929. A certain inquirer, he states, "need not regret the absence of any notice of the paper polisher from my book and my letters on speculum working. He evidently has no experience of it. It is just one of those things which appeal to the beginner and especially to the lazy one, who eagerly seizes on the idea, exclaiming, 'How lovely and simple.' It is such a contrast to the nasty messy pitch.

"In actual fact the paper polisher is everything that a polisher should *not* be. It has no yielding surface to embed and swallow up particles of grit. Consequently there are very few samples of rouge which will not leave a mass of ugly scratches on the mirror, if used with a paper polisher. Another objection is even more serious, and is fundamental. We know, I suppose, that the conclusion of fine grinding, if carried out with proper care,

leaves the mirror and tool with absolutely coincident surfaces; in other words, each is a segment of a sphere of the same radius. Now, if we paste a sheet of stout paper on the tool, it *is no longer of the same radius* as the mirror, but has a radius longer by the thickness of the paper. 'Oh, but what does the thickness of a sheet of paper matter?' It matters everything. We are dealing with quantities of the order of a millionth of an inch, when we figure a mirror, and therefore $1/100$ inch, or the thickness of an average paper, is a gross error. The net result is that the curves of mirror and tool are no longer coincident, and we infallibly get a turned edge. The paper, saturated with paste, is a hard and unyielding layer, which no pressure will persuade into coincidence with the mirror. The value of pitch lies just in the fact that it will yield to pressure, but slowly and regularly. A blow breaks it; but it flows under long continued pressure, and takes any required form that the operator has patience to give it. The first lesson which a beginner must learn, before he ever can hope to be a successful mirror worker is, **do not funk the pitch polisher. Master it.**''

Bell, "The Telescope," page 71, states that "cheap lenses are commonly worked on cloth or paper laps but that they leave microscopic inequalities which scatter light." He adds that all first class objectives and mirrors are polished on pitch. All good opticians know this fact.

A Cool Pinhole which will not toast the eye and face may be secured by reflecting the image of an ordinary pinhole by means of a small prism, as shown in Part I, Figure 18. Another method is that used by Hindle. Round and burnish the end of a piece of copper wire, about No. 20, and amalgamate the spherical end with weak sulphuric acid and mercury. The image of a distant lamp on the spherical surface forms an artificial star, which may be placed directly in the optical axis, with the knife-edge and eye immediately behind. Haviland uses a drop of mercury on end of a stick.

Permissible Distance Differential of Pinhole and Knife-edge along the Axis: If the pinhole and knife-edge are not maintained at the same distance from the mirror, will an error be introduced thereby? Apparently yes, but in practice no. Prof. F. L. O. Wadsworth analyzed this question in an article on the mathematics of mirrors (*Popular Astronomy,* August-September, 1902, page 345). He takes the case of a mirror of 50 inches focal length and shows mathematically that the knife-edge may be moved a whole inch nearer it or farther away from it than the pinhole before an error as great as the error of measurement (assumed to be 2 percent, though the uncertainty is likely to be greater than this). Hence in a mirror of any considerable focal length, an error of several inches in the relative placing of the lamp and screen will not affect the measurements by as great an amount as the average error of measurement itself. However, high and wide separation of pinhole and pinhole image will give a false monad shadow.

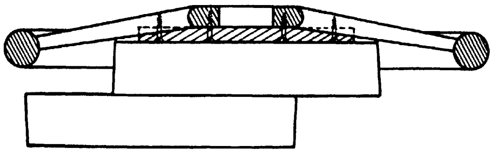
Turned-down Edge: If turned-down edge has been inherited from fine grinding the chances are that it is too gross to cope with by means of as fine an abrasive as rouge, short of vast labor, and a sad return to No. 400 or 500 Carbo is indicated. The pencil test, if carefully applied, should have

brought the disks close enough to sphericity to permit rouge to deal with the remaining discrepancies within reasonable time.

One makeshift way to avoid turned-down edge is to court its opposite, by reducing one or two of the edge facets—though a little of this usually goes a long way. It is relatively easy to keep a turning-up tendency within control, as described in another note (*"Turned-up Edge,"* below).

Too rapid strokes will often cause turned-down edge. The cause is the same as explained in an earlier note (*"Refusal of the mirror to become concave,"* etc.).

Turned Edge: Both in grinding and polishing, turned edge may result if the push-and-pull are applied too high above the plane of the work, which is the bottom of the mirror disk; likewise from too rapid strokes. Both sources have a similar cause. Source 1: If the push-and-pull are too high, as with a long handle like the one shown on page 288 when used carelessly—that is, when the force is applied far above its base or if it is actually grasped in the whole fist instead of acting merely as a centering convenience for the outspread hands—the tendency will be to lighten the load on the trailing side of the mirror and cause the leading side to plow in, rounding the edge. Source 2: If the strokes are too rapid the momentum of the moving disk will act as explained on page 344 (at bottom) and turn the edge, even if the force is applied low. Remember that, even if the force could be applied no higher than the top of the disk, the point of application would still be considerably above the actual plane of the work. Sometimes we are warned that long strokes will turn the edge, and therefore when we discover a turned edge we may resort to short, timid, mincing strokes, in trying to cure it. But, on hard laps at least, firm, fearless one-third strokes will often provide the cure when we finally "get mad at it."



A steering wheel dingbat used by J. V. McAdam, Hastings-on-Hudson, N. Y., for mirrors of medium size, and shown in his elevation drawing, applies the effort nearer the plane of the work, though the desire was also to provide a more firm, secure grasp than a knob or handle permits, and to facilitate handling a 12½-inch, 21-pound disk when off the tool.

Strictly speaking, no handle or knob is needed in mirror making. Professionals use none. The bare tool is held in the hands. Many amateurs who have accustomed themselves to working in this way wonder whether the handles or knobs were not used only because it became customary.

The Ronchi test will make very evident a slightly turned-down edge, in

fact few mirrors are made on which this test will not reveal at least some sign of it, even if no more than 1/32 inch wide.

Test for Slight Turned Edge: A. W. Everest contributes the following note: "A rigorous method of testing the perfection of the edge of the mirror is by diffraction, in connection with the knife-edge test. Lay a straight-edge against the mirror, in a vertical position. Bring the knife-edge across until the mirror completely darkens. At this point both edges of the straight-edge will be brightly illuminated by diffraction. At this point also, the right hand edge of the mirror will always be illuminated, either by turned edge or by diffraction, even if the edge is good. If the latter is the case, the left hand edge of the mirror will also be illuminated by diffraction. Now continue with the knife-edge until the illumination at the straight-edge just disappears and, if the illumination at the edge of the mirror disappears at this point also, the mirror's edge cannot be improved. If the illumination at the right hand edge of the mirror persists beyond this point, the mirror's edge is turned and will scatter light around bright star images.

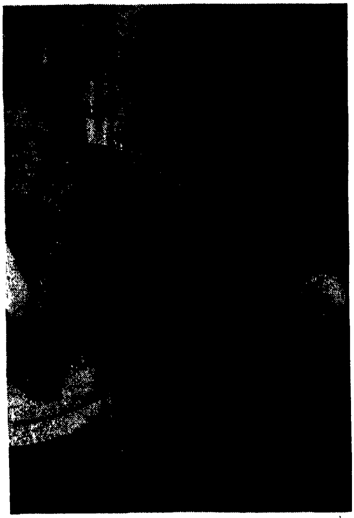
"It should be understood that the foregoing refers to that bright semi-circle of light which, with amateur workmanship, is usually seen under the knife-edge test on the side of the mirror toward the pinhole after the rest of the surface has completely darkened. In extreme cases, this illumination of the edge persists during *several inches* of knife-edge travel, and only most careful workmanship by an experienced workman will eliminate it entirely. But the beginner need not worry. If his mirror is mounted in a cell, the retaining flange will always cover the defect. If it is to be mounted in the open it may be fine ground for a few seconds on a piece of flat plate glass, using the finest washed grit obtainable, after which, lo and behold, it stands the diffraction test. If not, give it a few seconds more and test again. In bad cases it may be necessary to grind in 1/16 inch from the edge. This grinding is, of course, done after the final figuring operations and the writer's experience has been that it never upsets the figure."

Diffraction Effects: John H. Hindle contributes the following. "Diffraction is the cause of the bright rim at the extreme edge of the mirror disk, which is often confused with turned-down edge. By applying a *cleanly cut* mask, say, one inch or more smaller in diameter than the mirror, we can observe what a legitimate diffraction ring should be like. It is extremely difficult to get the edge of the mirror to conform to this standard, but that is what we have to aim at."

Another interesting diffraction phenomena mentioned by Hindle, Porter, and Everest, and known to most able telescope designers, is the fact that there will be fewer diffraction lines from a four-legged diagonal support spider than from one having only three legs. The reason is that each leg "reflects," as it were, a second diffraction effect from the opposite side of the mirror. Where there are three legs there will be six diffractions, so to speak. If there are four legs there will be eight, but four of these will then coincide with the other four, so that there will be only four diffractions net,

instead of six. A single support will give two. Everest spreads the effect around by giving the single support a scalloped edge. This does not rid the image of diffraction, any more than wearing a black shirt gets rid of dirt, but the psychological effect is comparable.

Turned-up Edge: This is easy to deal with. Invert tool and mirror and work on the edge of the mirror with the tool, but do so with discretion; that

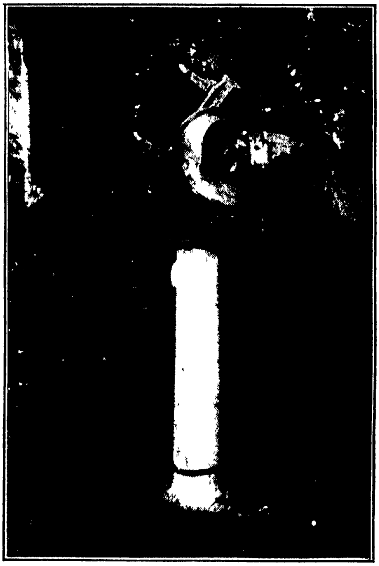


Mrs. Thomas A. Jenkins of Syracuse, N. Y., and "It," a 6-inch tubeless reflector made by herself. Up to 1932 three women were known to have completed telescopes.

is, do not apply the work at the very edge, for this probably would "bevel" it at the very outside without producing a uniform job. The best way is to make one or possibly two rather rapid revolutions around the pedestal, taking elliptical strokes in each of which the tool is drawn toward you at about three-fourths of the distance from center to the edge, and pushed back along a path half way or less toward the edge. A very little of this treatment will go a long way, and only a bit more will convert the turned-up edge into a badly turned-down edge.

Measuring Zones: Guarding against self-deception when measuring the radius of zones demands rigorous honesty. It is no more than natural that the worker should wish the mirror on which he has labored so hard to measure up as it ought, but it is virtually certain that if he knows beforehand where he hopes the marks will fall he will tend in some measure to

give the mirror the benefit of the doubt. We measure in the dark but we usually make the marks in the light and, of course, we cannot help but remember where we put the last one. Unconsciously obeying a kind of wish-fulfillment, we then tend to crowd the knife-edge toward the last marks when making the next measurement of the series. Instead, after each measurement of the three which usually are taken on each zone the knife-edge should be lifted some distance off the test-stand and put back in the dark, or in some other way thoroughly shifted, so that the location of the



A 12-inch Springfield mounting made by John M. Pierce, Springfield, Vt. It has a motor drive geared to sidereal time. There is an hour circle on the friction disk worm gear, with index marks on the angle casting and worm box cover. The latter is set to read correct star time on the hour circle, the motor is started and, thereafter, this index reads correct star time like a sidereal clock. The other index marks are set directly to the R.A. of the star. The brass worm wheel of this telescope gives it a distinguished appearance.

former marks will be lost and forgotten. One man wrote rather frankly, "I have tried this method but given it up, as I cannot make the marks come in the same place again" (!).

It is also best to measure the zones of shorter radius first. Then, when measuring the others, the base of the knife-edge will conceal the previous marks.

There are two ways of placing the knife-edge at the exact center of curvature of a zone. One, and possibly the better of the two, is to "bracket the target," as artillerists say. Shell No. 1 lands some distance behind you, then No. 2 lands some distance in front of you. You then know that No. 3 will land behind you again but somewhat nearer. No. 4 lands just in front of you, while No. 5 lands on your center of curvature—the entertainment being that you know, after No. 2, what is about to happen and can say your prayers. Bracketing thus, over and under, over and under, with the knife-edge, may be done quite quickly. No mark need be drawn, of course, until the center of curvature is found.

The second method is to attempt to sneak up on the exact center of curvature entirely from one side—*i.e.*, moving the knife-edge either away from you or toward you. Some can do this well, but if it is given a series of blind tests from both sides the respective marks are likely to show quite a spread; for it is not easy to say, when working entirely from one side, exactly when to "call it." However, the *average* of several tests by this method will generally fall just where the bracketing method may previously have placed the center of curvature.

Russell W. Porter was observed while testing a mirror; he took a long time—perhaps a full minute—for each measurement. But all three marks fell precisely on top of one another. Do not attempt to hurry the process.

Interpreting Shadows: Many a beginner (others, too) is stumped by shadows, often complicated, whose interpretation is equivocal but important. If the interpretation is really important enough it may be worth while to make special masks, isolating each doubtful area and actually measuring its radius. If the measurements themselves are right this method will give findings which admit of only one interpretation. Performing these measurements is something of a chore, but perhaps less of an annoyance than writing to someone a few thousand miles away and sitting down to wait a week or two for an answer.

Hole: Ellison gives practical directions (Part II, Chapter V) for doctoring a hill, but does not tell how to get out of a hole. One way is to remove the

Drawing by Russell W. Porter

How a hole looks. Invert the book and you have the appearance of a hill.

lap opposite the hole. It is necessary to scrape off only the thinnest possible depth of pitch. Then, the amount scraped off will fill in automatically by the time the hole is cured; but if not, the lap should be cold pressed before

going on. Shaving a lap just opposite any kind of depression is both a logical treatment and one that is usually effective.

A Testing Tunnel is any kind of structure—tube, box or what-not—surrounding the path of the rays to and from the mirror in testing. Especially in winter when there is likely to be a large temperature gradient between parts of the house, or on windy days in summer, such provision usually will render unsteady wavering shadows instantly fixed and steady, and thus on the whole it is very likely to conduce to much better results in mirror making. For testing large mirrors professional workers employ well built structures,

Neat, finished workmanship by W. F. Sprengnether, Jr., of St. Louis University, St. Louis, Mo., on a 6-inch reflector.

virtually long houses which are often double-walled, but the average small job may be tested in any single-walled structure of paper, cardboard, cloth or what-have-you, tacked over a few sticks, and this will often work wonders. It should, however, be quite tight, having no cracks larger than, say, 1/32-inch wide. It should be tightly closed at the mirror end, where some kind of door can be rigged up to give access to the mirror. The other end must be left open.

Testing without Masks: In routine tests of a paraboloid which are not final and critical, experienced workers generally do not bother with masks. At first it is somewhat confusing to test in this manner, but one soon becomes familiar with it. To place the knife-edge at the radius of the outside zone,

find the place along the axis at which a large half moon of shadow fills all except the outside zone in the right hand half of the mirror. It then will be observed that the entire left hand half of the mirror is illuminated. Of course we must ignore all except the outside zone—not seeing it, though it is there. The part of the outside zone on the right lies next to a dark shadow, hence it is well demarcated, while on the left it lies next to a high light (actually the reversed counterpart of the shadow), with no intervening demarcation, and on this account it appears to be a part of the adjacent high light. This will perhaps be confusing at first. We are now approximately at the radius of the outside zone and by a little closer adjustment, so that the whole zone all the way around darkens simultaneously and evenly, we can arrive at its radius.

All this is precisely what happens when we find the same point with the aid of a mask, though only a couple of patches of light are then actually visible and we may think of it in a different manner. Therefore an easy and instructive way to make the mental transition between the two methods of testing, and become familiar with the appearance without masks, is to find the radius by the more familiar means of a mask and then, without disturbing the knife-edge, remove the mask and study the mirror until the real (*i.e.*, whole) appearance is familiar.

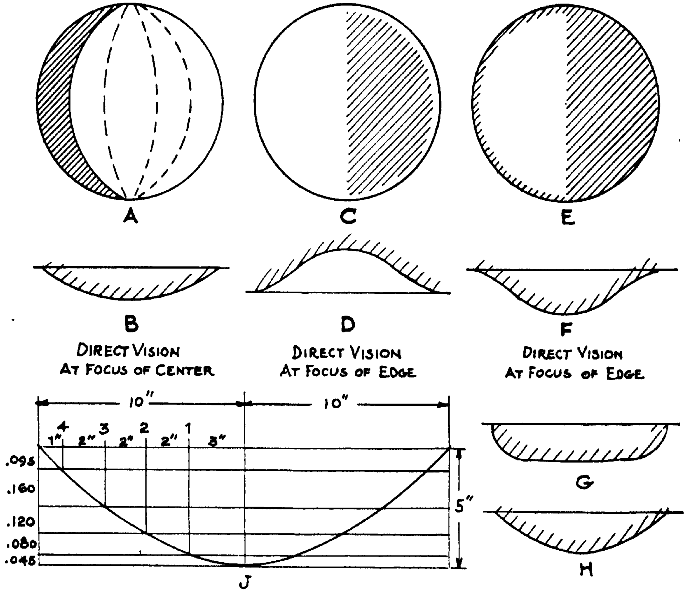
Having found the radius of the outside zone, again the simplest way to find that of the inside zone without a mask, until the method has been learned, is to find it by means of a mask and then remove the mask. We now note that, when we have the knife-edge at the correct place along the axis, the shadow starts at the left, as a slender new moon, spreads or widens at first slowly, then more rapidly to the right and, as the central zone is approached, it takes a comparatively sudden leap clear across. The same thing of course occurs when a mask is used, but most of the appearance is hidden.

When the worker reaches the point where he can test in this manner, and understand the reasons for the several phenomena observed, he may promote himself out of the rookie squad.

Masks for final tests are, however, advisable no matter how expert the worker has become in isolating zones without them, because no one ever becomes perfectly capable of ignoring the subtle influences of appearances adjacent to the zone being examined. Even in making a spherical mirror for some special use, if it is to be a really precise one, Hindle advises the use of masks. If there happens to be a very gradual, uniform transition in shade between two widely separated areas on a sphere this may "get by" unnoticed without a mask, whereas the same two areas would show their difference in shade by contrast if they were isolated by this means.

Hindle's Method in the Knife-edge Test consists in becoming accustomed to the appearance of the shadows, not when the knife-edge is half way between the center of curvature of the respective outside and inside zones, as is the orthodox method of viewing the paraboloid, but at the center of curvature of either the outside or the inside zone. The essential principles

are the same as in the more familiar test but, instead of the "Life Saver" curve which changes general direction four times, the curve is a single one. Workers who are already familiar with the regular test may find this variation interesting and instructive, as the interpretation of shadows from different points of view tends to limber up the mind and give added confidence and familiarity with testing in general. The following description is from *English Mechanics,* November 16, 1928:



Drawings by Russell W. Porter, after John H Hindle and *English Mechanics*

"Assuming we have a parabolic mirror under test with this apparatus, what do we see visually? The reply is, it all depends where the knife-edge cuts the cone of rays. The longitudinal distance along the axis of the cone to which the knife-edge can be usefully applied is bounded by the radius of curvature of the center of the mirror, on the inside, and the radius of curvature of the outer edge of the mirror, on the outside. Let us first of all examine the mirror at the focal point of its center. See *A*. The knife-edge is presumed to pass from left to right, and in noting the passage of the shadow, the eye follows the same path as in reading these lines. The hatched portion shows the shape of the shadow as it first impinges on the

mirror, and the dotted lines the shape its outline assumes as it progresses across the mirror, being vertical, even if somewhat unstable, in the center. The apparent shape of the surface is that of a solid seen in section in *B*, the center being nearest the observer, and falling away evenly on all sides. As we 'fling' the shadow across this projecting convex surface, the slightest irregularities become visible, and any changes of curvature can be instantly seen. The oblique illumination is from the right, and it is impossible to mistake the nature of any irregularity seen.

"When we pass to the focus of the outside edge, we may recognize when the knife-edge is in the precise position in the following manner. A point along the axis is chosen where the shadow forms as in *C*, that is to say, it all but fills the right half of the mirror, being only a little short of the vertical center-line, and not quite touching the right-hand outer edge. The position chosen is a correct one if, with a further minute movement of the knife-edge, the appearance indicated in *E* is obtained; that is to say, the previous shadow expands to entirely fill the right half of the mirror, and simultaneously a narrow and delicate strip of shadow appears around the left hand rim. This position can be fixed with about the same accuracy as an ordinary zonal test with diaphragms (assuming a normal edge to the mirror free from turn-down). If the knife-edge is too far forward the strip of shadow on the left hand edge is too wide. If the knife-edge is too far back the strip of shadow does not appear at all before the whole of the right hand half of the mirror is obscured.

"Bearing in mind that the proper position in which to assume the oblique illumination is, on the side toward which the knife-edge is traveling, the section of the imaginary solid we see is shown at *D*, but it is possible, and indeed, probable, that we may see it inverted, in which case it would appear, not as a depression but as a protuberance, as shown at *F*. I prefer this method of viewing it. The shadows seem to show up the shape of the imaginary solid much better, and irregularities are better estimated. But it is absolutely essential to know that we see the thing inverted.

"Having now ascertained the method of accurately locating the foci of the center and of the edge, we measure the distance between the two points, and this is the well-known r^2/R. It is of course greater than the sum of the zonal differences, but can be made to fit in with the latter, as well as providing an excellent check on their accuracy. If the appearances indicated are obtained with mirrors whose apertures are $f/8$ and upwards the use of diaphragms may be dispensed with. On short-focus mirrors, however, although the total aberration may be right, it may not be correctly distributed from edge to center. Strictly speaking, the shape of the apparent solid at center focus will show this. If the correction is too great in the outer zones we get an appearance like *G*, and if too great in the central zones, more like H.

"The apparent solids seen are sketched from a mirror of aperture $f/5$ or rather less, and in consequence the following method is suggested to the beginner of ascertaining what his mirror should look like at central focus (*B*). On a squared paper draw the mirror full size, then calculate r^2/R

and multiply it by 10. The zonal differences are also calculated and similarly increased, enabling us to plot the curve shown in *J*, in which are shown precisely the relations of the various quantities referred to. For a 20-inch mirror of 100 inches focal length the figures given below apply.

"A careful study of these figures and of the diagram will give a clear conception as to what a parabolic mirror really should be. 'Turned edge,' which usually exists between the outer zone and the edge, immediately becomes apparent by measurement. No special attention need be paid to the appearance of the shadows at any other point than the two indicated. There, they have a definite form independent of the relation between diameter and aperture, and can be utilised, not to supplant the zonal test entirely, but to supplement it in a most useful and efficient manner."

Zone	Radius	r^2	$r^2/200$	Differences
center	0	0	0	
1	3 ins.	9	.045	.045
2	5 "	25	.125	.080
3	7 "	49	.245	.120
4	9 "	81	.405	.160
edge	10 "	100	.500 to center	.095

The Slit Test is simply a glorified test with the pinhole. If instead of one pinhole there are two, one above the other, it has been found that the shadows will not be altered. There will, however, be better illumination. This in turn will make feasible a reduction in the size of the individual pinholes and thus it will effect a gain in sensitivity of the test.

The above being granted, why not carry the same idea further and use three pinholes in a vertical row? Or use five or ten, or any number, reducing their diameter in proportion and thus gaining that much more in sensitivity? This, too, will work without trouble and the shadows will remain the same.

If this be so, why not interconnect the pinholes of the chain, creating a slit, as this would not affect the principle involved. This is the slit test.

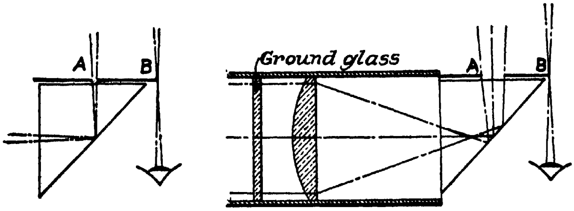
The increased illumination affords a corresponding reduction in width of the slit; or a compromise will permit both some increase in sensitivity and better illumination. One method of making a narrow slit is described in the chapter on the Ronchi test. The knife-edge must be maintained parallel with the slit. A large pinhole is the equivalent of a slit, as a simple experiment will indicate. Set the knife-edge at the average center of curvature of a paraboloidal mirror, or where a spherical mirror is about 50 percent darkened. Then, with a magnifier, examine the cone of rays at the knife-edge. The cone is not bisected on the vertical median line, as might be expected, but only the edge of it passes beyond the knife-edge. Also, if a larger pinhole is used the width of the passed part will be the same when the conditions mentioned above are arranged but, being from a larger circle, it will more closely resemble a slit. Despite these facts, a very narrow pinhole will give greater refinement, for the same reason that a very narrow

slit would do the same. The slit, of course, would give the better illumination of the two, width for width.

If it is desired to have equipment for special work, such as locating astigmatism with a diagonal cut-off, or when testing a flat in combination with a sphere, some means for rotating the slit and the knife-edge, and at the same time maintaining the two in strictly parallel position, must be provided—either doing this separately with graduated dials on each part, or gearing the two parts together.

The origin of this test is difficult to assign; in a measure it was a growth. Russell W. Porter suggested it in 1918, but did not actually try it until 1931. At about the latter time two amateur telescope makers, James C. Critchett of Julian, California, and Daniel E. McGuire of Shadyside, Ohio, each hit on it independently.

"The slit and knife-edge can be combined by covering the square face of a small right-angled prism with a rectangle of tin-foil," Russell W. Porter



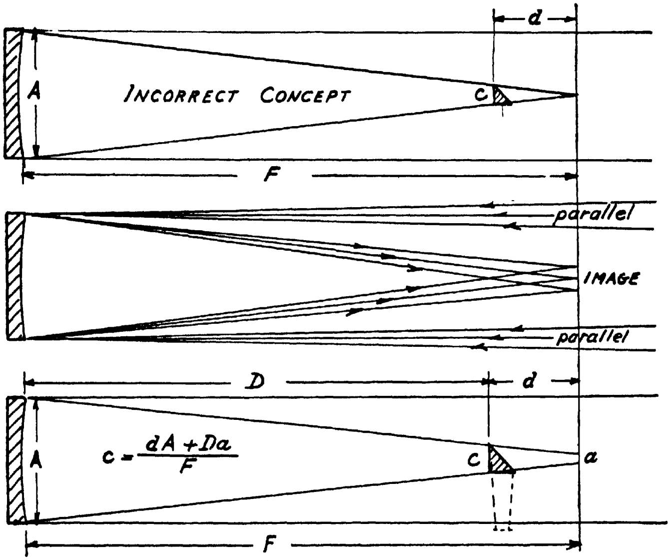
adds. "The slit is formed in the foil at A, and the edge of the foil at B serves as the knife-edge, as shown in the left-hand sketch. Of course B must be cut parallel to the slit. For diagonal cut-offs the whole unit—lamp, prism, slit and knife-edge—must rotate as a unit about A as a center." This is the application of the slit test said to be used by Dr. Samuel Jacobson, in charge of optical work for the Gaertner Scientific Corporation.

To the last statement Professor Arthur Howe Carpenter of the Armour Institute of Technology, Chicago, adds: "Dr. Jacobson has shown that it is not essential to have a narrow slit at A. It should at least be wide enough to give plenty of light, which is a great help in finding the image at the observing stand (right hand sketch) where a means of getting uniform illumination is indicated. Dr. Jacobson simply ground the side of the quarter-inch right-angled prism and allowed the diffused light so obtained to illuminate the whole thing without the use of condensers. That part of the prism to the left of A may be left uncovered and a single piece of tinfoil used, so cut that the two edges are parallel; or the left-hand side may be covered, leaving a wide slit at A. This is better for obtaining uniformity of illumination. When the prism with the illuminated opening and knife-edges moves as a unit toward the image, the latter, of course, moves toward the knife-edge, disappearing behind it until the shadow of the knife-edge (or

right hand side of the slit) at A approaches the knife-edge at B. With a delicate screw control this can be made to give any width of slit desired. Dr. Jacobson states that, in this way, he uses two smooth straight knife-edges in place of the edge of the usual pinhole which is seldom smooth. Fine pinholes are likely to have jagged edges and, even when perfectly smooth, they easily collect dust particles and are troublesome to keep clean, giving erroneous appearances to the surface of the mirror. I have my apparatus so arranged that I can use a slit, a wide opening or a pinhole at A, as I wish, and use a knife-edge at B. My observation is that a clean-cut fine pinhole, properly illuminated, will give everything which these slits will give, up to the very final work; after which a fine slit with very smooth straight edges is an advantage because of the extra light which it affords. The Jacobson scheme, in common with all slit tests, is extremely sensitive in focusing, and is very delicate. Unless the worker is very careful to obtain the exact focus, a slit will give misleading results to one who is accustomed to the pinhole test. The point in the Jacobson arrangement is that no mechanical slit is used or needed. The shadow of one knife-edge meets the real knife-edge and forms a slit. A single two-edged safety razor blade may be used as the edges are parallel and smooth." [Use $r^2/2R$ here.—Ed.]

Finding What Sized Prism Will Be Needed has puzzled many workers. Unless one is on his guard there may be danger of drawing up a concept like the one in the first of the sketches (p. 382), being misled perhaps by Figure 3 or Figure 19 of Part I, which are supposed to be only diagrammatic. Here the method would be one of simple proportion between similar triangles, that is, c is to A as d is to F; solve for c. This would be the correct method if all the rays which reach the mirror from the whole field of view were parallel, but they are rarely so. They would be parallel only if they all came from a single point; for example, if there were only one star in the heavens. Instead, most of the rays which are made use of come in at a small angle with the axis of the mirror (up to about 15′ in an $f/8$; more in $f/6$) and these "out-of axis" rays are reflected somewhat as in the second sketch, combining to form an image. This is the reason why the opening at the top of the tube should be a little larger—say ¼ inch or, still better, ½ inch—than the diameter of the mirror, though if it is not, the loss will be small at worst. This image has real diameter, as shown in the second sketch—it is not just a point—and this diameter is *assumed* to be the diameter of the field lens of the eyepiece of longest *e.f.l.* used. In practice this is ⅞″ for a 1″ eyepiece. The image in a small $f/8$ mirror will be just about that diameter; in an $f/10$ or $f/12$, or a large $f/8$, it will be larger but the excess will not be caught by the field lens, anyway, unless a rather unusual eyepiece is used, so ⅞″ is the outside diameter to figure on in all but exceptional circumstances—eyepieces of long *e.f.l.* which in turn have a wide field lens and other undesirable characteristics. This alters the triangle of our original sketch to a trapezoid, as in the third sketch, and the formula for finding the diameter of the prism face, as given by John M. Pierce, is shown on the same sketch. Figure to center of hypothenuse of prism.

The above is the geometrical method but some may prefer the less high-brow but safe, sure, practical method, which is as follows: The mirror is set up in strong sunlight and adjusted until its own optical axis points pretty closely at the sun, that is, when the image of the sun is caught on a card and at the same time the shadow of the card falls on the middle of the mirror. It will now be simple to explore with the card the whole length of the cone of reflected rays and actually see what's what by means of the



Drawing by Russell W. Porter, after the author

illumination. It is easy to measure the diameter of the cone at the desired distance from the mirror or from the focus. One way is to lay off on a long stick the offsets and distances required by the mounting and hold the stick beside the cone. Rings of several diameters drawn on a card will enable one to get a close enough measurement of the size of prism face required, as the image will approximately fit one of these rings. If a simple flat of elliptical shape is to be used the diameter of the circle obtained should be multiplied by 1.42 in order to derive its longer dimension.

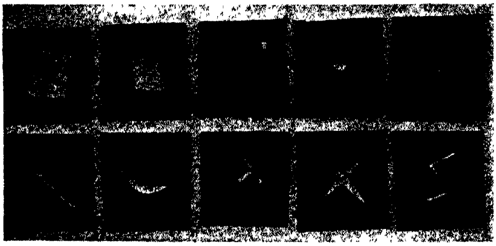
There has been some confusion regarding whether the sun is a fair criterion for a field of stars. On a mirror having a focal ratio of approximately $f/8$, the field of vision will have an angular diameter just about equal

to the sun's angular diameter, namely half a degree, and it makes no difference whether it is the sun or a field of separate stars which subtends the same angle.

The discussions presented above are based on *practical* facts, but in theory there is a certain variation—which, however, will lead us to the same method of working, hence the beginner may safely ignore the following: Strictly speaking, the sharply bounded image depicted in the second drawing does not exist in fact. As Porter points out, this is only *that part* of a much wider image which is *useful*. We may look at it in this manner: The rays which enter the tube at the edge, and reach the mirror at the center, are reflected out of the tube past its opposite edge. Similarly, others which enter the tube at a small distance from the edge are reflected back and out, unless captured and put to work; though diagonal rays which reach the edge of the mirror will, of course, be reflected against the inner walls of the tube and come to naught. Together, all of these rays, as can be worked out in a simple sketch, will form an image of a fairly wide area of the heavens—several degrees in width—which extends clear across the tube, and if there is no tube, or if there is a skeleton tube, this image will take the shape of a whole dome, extending right down to the "horizon" of the mirror. We cannot very practically pick up this whole image with our diagonal, because of its size, and in practice we do not even wish to; first because the best of its rays are already concentrated near the center where we can conveniently capture them, the edge illumination thinning out to a minimum; secondly, because the spherical aberration that far away from the axis would be rank. The field lens of a 1-inch eyepiece is about ⅞-inch in diameter, and this in the average case and, in fact, in nearly all cases, will take in the *useful* part of the image. Hence we get back to our starting point; namely, that the size of the prism may be based on the considerations depicted in the second sketch—the ⅞-inch diameter of the field lens of the eyepiece is the governing factor. Of course, eyepieces have been made with a field lens several inches in diameter, but only for some very special purpose or as a freak, hence this point has little practical bearing on the issues under discussion. The ⅞-inch is not merely arbitrary. It is the accepted result of long accumulated experience.

Focal Lengths, Size of Image, Focal Ratios: With a given focal length, no matter what the diameter of the mirror, the diameter of the image of the same object or field will always be the same. We might look at it in this way: Diaphragming out the outside zone of a mirror does not alter the focal length of the remainder; nor does diaphragming out any part of the mirror, regular or irregular, do it; for example placing your hand in front of the telescope. What these things do is to reduce the *intensity* of the illumination. Looked at from the opposite point of view, whenever we want to get more illumination, as in looking at or photographing faint objects such as nebulae, etc., we design a telescope having a larger mirror of the same focal length. (It is true, this then gives a shorter focal *ratio,* but that happens incidentally.)

If the above is true, the logical reader may next ask: "Would it then make any difference if I were to use a smaller prism than geometry or the test on the sun indicates, and thus save money; for this would have the same effect, would it not, as diaphragming out a part of the light nearer its source, namely, before it reaches the mirror? In other words, by *reductio ad absurdum,* would not in fact a very tiny prism of *any* reduced size, catch and reflect a complete image?" It would. This is because every point on the prism receives rays from every point on the object, reflected from some part of the mirror (provided our tube is enough larger than the mirror to allow the marginal rays on one side to reach the very edge of the mirror on the same side). What we should then get would be a complete image but reduced illumination. This, too, may easily be tried as an experiment on any reflecting telescope, simply by diaphragming out parts of the prism with paper, as was actually done to settle an argument (See photograph of a group of such diaphragms of black cardboard).



"Then, if you grant this much," the same reader persists, "what is the use of buying a prism large enough to take in the marginal rays of the image? For there is enough illumination from the moon by which to see it; generally, in fact, with a low-powered eyepiece there is some to spare; and when using a high-powered eyepiece the whole of the moon's disk cannot be seen at one time, anyway; while there is no question at all regarding sufficient illumination from the sun."

The answer is, that there will be no practical gain in having a full-sized prism when using a low-powered eyepiece on the moon; in fact a diaphragm, or an effective diaphragm (smaller prism) somewhere is then a good thing, because the observer who stares long at the moon with such an eyepiece generally wishes he hadn't, for he becomes temporarily moon-blind; while the sun is so bright that it will give no cause in any case for concern about husbanding light. But with the *high-powered* eyepiece on the moon any kind of diaphragming out, including the use of too small a prism, will reduce the illumination, even on that part of the image which the high-powered eyepiece takes in. The same will be the case when examining a field of stars or faint nebulae with any eyepiece, for here we need all the illumination we can get. In effect, the reduced prism is at such times a *reduced mirror,* hence a smaller

mirror might better have been made in the first place. Therefore a prism large enough to take in all of the rays that will go into the field lens of a one-inch eyepiece is desirable; but a smaller one will only relatively cripple the telescope—this is the sum and substance of it.

Going on to other cognate considerations, the shorter the focal length the smaller the image, say, of the sun, regardless of diameter of mirror. Now, suppose we wish to compare two mirrors of different focal ratios but giving images of equal diameter. The focal lengths must therefore be the same, for the different focal ratios mean different mirror diameters. A mirror having twice the diameter of another mirror will illuminate its image four times as brightly, but it will not magnify more unless its focal length is increased.

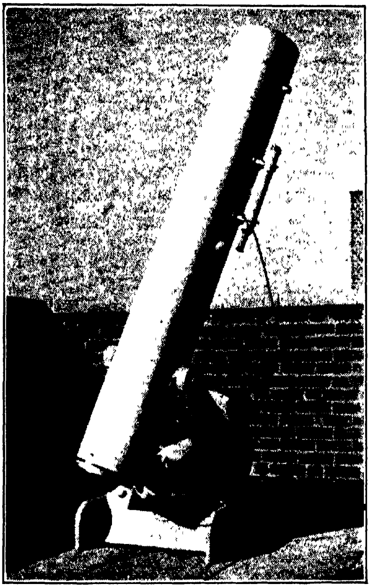
Finally, suppose we demand both a larger image *and* brighter illumination: We must then increase both the focal length and the diameter; in other words we must acquire a larger telescope of the same focal ratio.

Thus there is no way to beat the game. You do not succeed in eating your pie and having it too.

In Chapter VI of Part II Ellison recommends a focal ratio $f/8$ to $f/9$. Many amateurs have requested further reasons for this recommendation. In *English Mechanics,* May 6, 1932, Ellison makes further comments, as follows: "I recommend $f/8$ because it combines the easiest figuring with capabilities for excellent performance. To go below $f/8$ is to sacrifice some performance, and to have difficulties with eyepieces. Achromatic eyepieces are the only ones which are satisfactory with short-focus mirrors. With long-focus mirrors, ordinary Huyghenian eyepieces are almost as satisfactory as they are with refractors. But *if you can get a really excellent mirror of* $f/10$ or thereabouts, its performance has to be seen to be appreciated. Its star-disks are just as good as those of the finest refractor, and the use of shallow eyepieces is a great comfort. You need not go searching the opticians' shops for 1/6th and 1/8th inch eyepieces, and mostly not getting them, nor paying fancy prices for German goods, in the endeavor to raise a high power, or to get the best out of your telescope. And you get a lovely flat field. All this, of course, at the expense of a foot or two longer tube, and more cubic space for housing. Among the advantages of long focus is that a smaller flat is needed, with less loss of light and less diffraction effects."

Dr. A. Woolsey Blacklock of England, for many decades a well-known amateur telescope maker, says in *English Mechanics:* "The focal length of a speculum is a matter of compromise. Eight diameters is probably the best proportion for those that are less than ten inches in diameter. If two mirrors that are equal in diameter are compared, one having a focal length of eight diameters, and the other twelve or sixteen, it will be found that the mirror with eight diameters shows stars with smaller spurious disks than the other whose focal length is longer. But if the focal length is reduced to six diameters, the diagonal plane must be larger, and this injures definition by increasing the diffraction rings round the disks. This increase of size in the plane is due to the fact that it must be closer to the mirror, where the cone of converging rays is larger. We have to allow for half the diameter of the

mirror, the thickness of the cell, the free space between the cell and the tube, the thickness of the tube, which may be a wooden one, and three or four inches for the sliding tubes or rackwork for the eyepiece. Altogether these will require the plane to be placed about 1½ diameter of the mirror from the focal point of the cone of converging rays, or 4½ diameters from the surface of the mirror. As the plane must be a little larger than the image



An excellent mounting made by Charles W. Eliason, of Chicago. This is somewhat similar to one shown in Ellison's The Amateur's Telescope and to the 60-inch telescope at Mount Wilson. The polar axis is a stub shaft at the center of an ordinary 24-inch wooden pulley. The latter rotates on two 4-inch rollers, similar to those of the Porter split ring equatorial mounting.

of the large mirror that is reflected in it, its minor axis must be about one third of the diameter of the large one, and its cost increased correspondingly."

A telescope having a focal ratio $f/5$ or $f/6$ is extremely sensitive to focus and requires a very fine figure.

Ainslie (*Journal B.A.A.*, Nov., 1930) states that the ill effect of the short focal ratio varies inversely as the square of the focal ratio; that is, it would be four times as bad in an $f/4$ as in an $f/8$.

Finally, figuring a short focus mirror is very much more difficult than one of medium focal ratio, and much the same may be said of a long focus mirror.

When Shipping a Mirror a relatively small amount of packing material in the right place will serve better than wrapping it in a whole mattress. First, the face should be protected from rubbing against any loose packing, if any is used, while on the journey when the train will constantly jiggle the disk. Ellison received a mirror which had thus jiggled itself into a figure which required six hours of polishing to restore. Soft paper taped on the disk will move with it within the outer packing and prevent this kind of abrasion. A flat board laid against the face will bridge the concave surface, as will the cover of a round tin marshmallow box—an ideal cover, by the way, for protecting the mirror under some other circumstances. Outer packing need not be thick if it is properly bestowed. A glass disk will withstand a heavy blow on the middle of the back or at the middle of the edge, but a light blow near any of the edges will remove a big chip. Throwing or dropping the containing box ten feet, which must be expected in the mails, may deliver just such a blow on the edge, despite much packing of a loose kind through which the disk may have gradually burrowed its way toward the outside while en route. In a test, a mirror surrounded by a snugly fitting round wooden cut-out, or a square with a board screwed across the grain on either side, and no other packing, would take altogether more bumps without injury than another disk done up loosely in a whole feather-bed; in fact it would be rather difficult to damage a mirror thoughtfully packed in the former manner, simple and compact as it is.

Effect of Falling Temperature on a Mirror: Not all are wholly agreed that a mirror should be left undercorrected. This matter has been debated with exceeding vigor. Ritchey's statements support Ellison, and so do Plaskett's, in Volume I, No. 1, of the *Publications of the Dominion Astrophysical Observatory*, with regard to the "edge effect"—curling up of the edge zone and consequent shortening of its focal length. See also *Transactions of the Optical Society*, Vol. 26, No. 4, pages 217, 223, 225; but see page 230. However, there is support for another point of view in the Plaskett paper, with regard to zones farther in; the mirror in question was the 72-inch and this has a perforated center, a fact which may have complicated the issue. Pettit, in *Mount Wilson Contributions*, No. 226, throws some indirect light on the question but, as in nearly every other published case, the circumstances are not typical—the effects noticed are due to heating up by the sun and the mirrors are partly flats. Mirrors, each one of them, seem to be a law unto themselves.

Ellison, in Part II., when recommending a 75 or 80 per cent correction, plainly has in mind mirrors of about $f/8$, which he recommends the amateur to make. In *English Mechanics*, Letter 525, 1926, he says, in speaking of Wassell, "He expressly recommends two-thirds or three-fourths of full parabola as a good correction. I believe in correcting much closer and, in the case of short foci, going right up to the parabola." Elsewhere he speaks of a mirror of $f/6.8$ as short focus, thus indicating what he regards as such.

Porter and Hindle recommend exposing the back of the mirror to the

open, outside air, insulating the edge with paper, cork or a strap, and giving the mirror full correction—that is, figuring it to the parabola.

A great deal more might be written and, indeed, has been written, without settling this vexed question with the kind of finality which all will accept. It seems possible that, as in many another argument, a large part of the spread between the respective views may be accounted for by the fact that the debaters are not really arguing on exactly the same premises.

One thing does seem reasonably certain: It is probably unsafe optics, even if it looks like good logic, to sit down and attempt to *reason* out, especially by some apparent analogy such as that between the behavior of a cooling mirror just off the polishing lap and one in a telescope, what a mirror "ought" to do. Mirrors have a polite way of thumbing their noses at "ought-to-do." Mirrors, behave as they behave, not according to any universal law but probably because each one is different in at least some of the following: composition, annealing, size, thickness-to-diameter ratio, insulation, focal length, situation in the telescope, time and circumstances of use, and probably other factors. There are too many unknowns in all this welter of conditions, too many subtleties, to permit working out anything like a resolution of forces which will give a dependable dogma. Observation is the remaining recourse. Evidently this, too, gives contradictory answers in many cases. The skein is tangled.

One point which Ellison has emphasized is that change in figure occurs only *during* change in temperature—"It is chang*ing*, not chang*ed*, temperature that has the effect I have so often described. A mirror which is truly corrected at 50° F. or 60° F., will also be truly corrected at 100° F., and equally truly corrected at 20° F. It is during the process of changing from one temperature to another that its correction alters."

Making Focograms: Harold A. Lower, who has made excellent focograms, tells how it is done in the following note, written by special request: "It is easy to photograph the figure of a mirror by placing a camera a foot or so back of the knife-edge. No lens is needed. The only precaution necessary is to see that the test lamp is well shielded so that no light will reach the film except that which is reflected from the mirror.

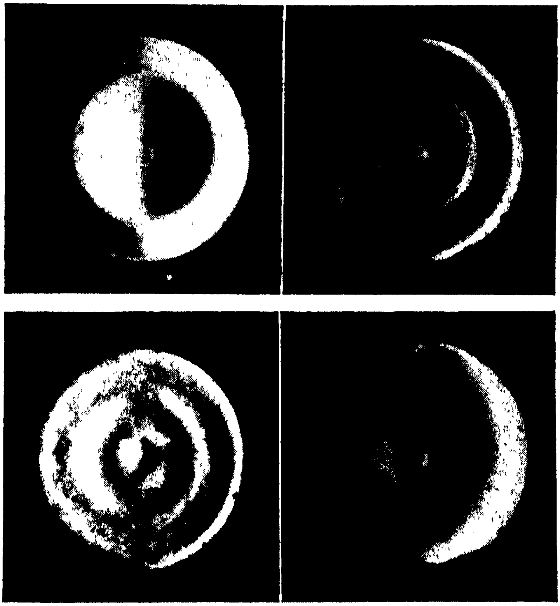
"Panchromatic film should be used, and the exposure for an unsilvered mirror need not be long. About three minutes, for a first trial, should be near enough right. If the negative is thin, double the exposure next time. If too dense, cut it in half.

"The image of the mirror may be seen on a white card, held a few inches back of the knife-edge. When the knife-edge has been adjusted until the image of the mirror looks right, make the exposure by moving the card out of the way. A little experimenting will soon enable one to make an exact record of the figure of his mirror at any stage.

"One is not likely to have difficulty, except with mirrors of short focal ratio, when the knife-edge and pinhole must be close together or the mirror will appear warped in the focogram. However, this is true of visual testing,

so photography does not add any new problems. Panchromatic film or plates are used because they are faster."

Lower's method of making focograms is essentially the one which was described by Porter, though in less detail, in June, 1918 (*Astrophysical Journal*). The lens is removed from the camera.



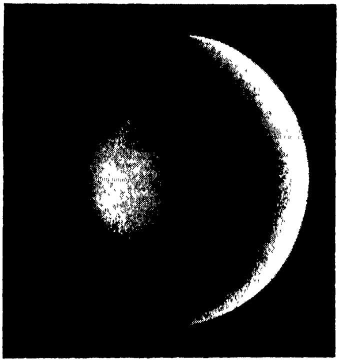
Four focograms made by E. Lloyd McCarthy, showing progress on a recalcitrant mirror which was finally brought to book. Mirrors, like youths, usually pass through a few of these "unlicked" formative phases.

In the first focograms the lens was retained in the camera. (See Hartmann, in *Zeitschrift für Instrumentkunde,* Vol. 29, 1909, page 217, and in *Astrophysical Journal,* Vol. 27, 1908, pages 237 and 258.) This is the method used by E. Lloyd McCarthy, who makes the following comments: "I have found it necessary to mount the camera on a bench entirely separate from that supporting the knife-edge and pinhole, as the most minute jarring causes the shadows to disappear. I use regular Verichrome film and find that the exposure for the unsilvered mirror may vary from 10 seconds to 20 minutes. The former is sufficient for a bad figure but, as the figure approaches the sphere, up to 20 minutes is required. A ground glass at the

back of the camera is a help in telling beforehand whether one may expect to find anything on the developed negative, but a puff of smoke near the camera will reveal the path of the light and tell you whether or not it is all entering the lens. See that no light escapes from the lamp except through the pinhole, or else there will be reflections from the back of the mirror."

Focograms provide an excellent method of comparing mirrors when at a distance. It is fervently hoped that focograms will be substituted for some of the free-hand sketches of shadows which are submitted by mail for diagnosis of mirror trouble. Focograms are admittedly more troublesome to make than hand sketches but they tell far more than the latter.

Curves: The discussions which follow treat the curves which are found on a mirror at various stages of figuring, and which are frequently mentioned in the special literature of mirror making, in a naturalistic, non-mathematical manner, because there has been a call for such a treatment. They are *not* intended for the worker who has had the good fortune to study analytic geometry. Such workers will find a far superior treatment in their own familiar textbooks. There are, however, to judge by the Editor's mail over a period of years, many workers who either have had no opportunity to

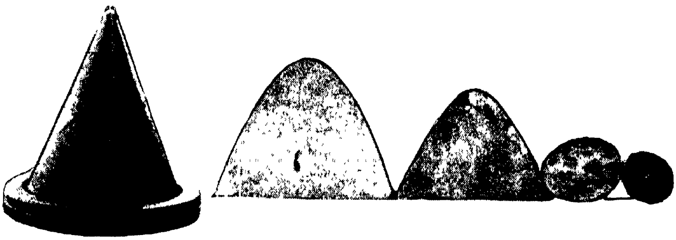


Focogram of a 12-inch mirror (95 per cent of r^2/R) made by Harold A. Lower. The heavy contrast in shadows is due partly to the short focal ratio (f/6) of the mirror, and partly to the difficulty of preserving the original delicacy of shadow through the various engraving and printing processes.

pursue higher mathematics or who are not naturally mathematically minded, yet who would welcome some simple attempt at treatment of these curves. It is felt that these same workers will not demand or even desire that such a treatment conform to all the pedantic peccadillos of the blackboard type of theorist, and they doubtless do not care whether the lingo is that of the corresponding type or not, for they are not preparing to become mathematicians but mirror makers.

As we saw on page 12, the curves to be found at different times on a mirror may also be found on a cone cut by a plane. A cone of wood similar to the one shown on that page may easily be turned up on the lathe and then dissected to reveal the nature of these curves, and is a nice plaything to possess if the parts are detachably pinned together with dowels.

At some convenient height (near the top, thus leaving room below for other things) a saw-cut is made horizontally. The intersection is a circle. A second cut is taken, beginning anywhere along the side, and parallel to



A wooden cone at Stellafane, for demonstrating the conic sections. At left is the assembled cone on its base, showing the intersection lines. (The vertical line at the left is an opened joint in the wood and may be ignored.) At right are four parts of the cone—respectively with a hyperbola, the parabola, an ellipse and the circle at intersections.

the opposite edge. The intersection is a parabola. A third cut, steeper than the last one, is taken for practical reasons—to favor the wood—some distance below it. This gives a hyperbola.

Any cut (less steep than the parabola) between the circle and the parabola will give an ellipse.

Any cut (steeper than the parabola) on the other side of it, will give a hyperbola.

Thus there are an infinite number of shapes and sizes of ellipses. There are likewise an infinite number of shapes and sizes of hyperbolas similarly derived.

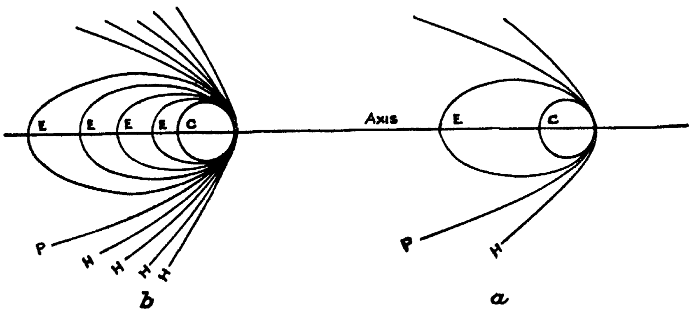
Of parabolas we can obtain an infinite number of sizes by cutting an infinite number of cones of increasing sizes, but there is no way to obtain more than one *shape* of parabola for there is only one shape. The same is true of the circle.

It is usually difficult at first to believe this statement regarding the unique shape of the parabola, so let us try to break it. We shift the cutting plane bodily to the left in the drawing (page 12) until it almost reaches the opposite edge of the cone. Manifestly the parabola we now obtain will be long and relatively slender, quite unlike our original parabola in its superficial appearance. Yet it is the same curve and the larger parabola would have a shape analogous to it if its arms were suitably extended. True, the one parabola would be larger in size than the other, but their shapes would be

the same. Another attempted dodge would be to make the cut on a cone a mile, or a million miles, high. But, no matter what we do, if the arms of the one curve are suitably extended, or if those of the other are suitably cut off (which is legitimate so long as the shape is preserved), the two will look alike, and if one of the two is then magnified, or if the other is reduced in size without changing its shape, the two will coincide exactly when superimposed. The actual curves on a typical telescope mirror may be regarded as if taken from low squat cones, say 60 feet in diameter and only an inch high, or else as taken from exceedingly limited parts of higher cones near the vertex and magnified—which in either case amounts to the same thing.

The parabola is the infinitesimally thin boundary between all the infinite number of ellipses on the one side and the infinite number of hyperbolas on the other.

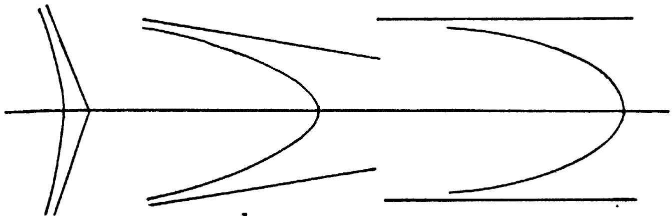
A set of these curves, if suitably chosen, can be made to nest neatly together like *a*. The point where they touch is the vertex. The same set or "family" of curves may be increased in population, as it were, by slipping in a graduated series of ellipses and hyperbolas, as in *b*.



Drawings by Russell W. Porter, after the author

Starting with the circle, and at the common vertex of the curves, its "arms" may be said to return to one another most quickly of the lot. As we proceed through the ellipses these arms open out wider and wider. This means that the parts near the vertex, the part of the curve dealt with in practice on a mirror, will do the same. On the last of the ellipses, before coming to the parabola, these arms are not far from parallel. On the next curve, the parabola, the closed arms break open and the arms, as they are extended farther and farther, approach more and more closely to a pair of parallel lines, as at *c*. On the first of the hyperbolas the arms are slightly more divergent; they approach, though they never quite reach, two straight lines drawn at a very acute angle, as in *d*, and in subsequent hyperbolas they approach straight lines in a constantly widening "V" (see *e*), until the sides of the "V" are themselves finally in a straight line. The radius of all ellipses,

that of the parabola, and that of all hyperbolas, is shortest at the vertex and grows longer and longer out on the arms. The arms of a parabola are spread just enough to reflect parallel axial rays to one point (focus) from all points on the paraboloidal mirror. Those of the ellipse are turned in more than just enough to do this and an ellipsoidal mirror of the same family of curves therefore reflects its marginal rays to a point nearer the mirror than the rays from its center (under-correction; ellipsoid). The arms of the hyperbola are turned in less than just enough to reflect parallel

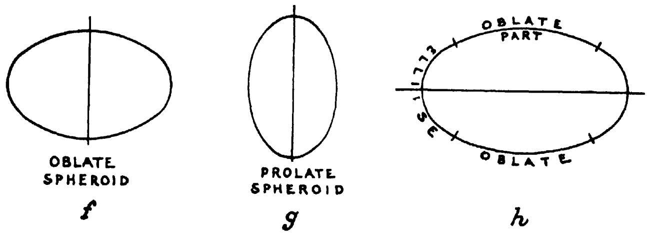


axial rays from all points on the mirror to one point, and here the marginal rays are brought to a point farther away from the mirror than the rays from its center (over-correction; hyperboloid). If this statement and the one previous seem to be contradicted by the fact that we deepen a mirror's center in parabolizing it, see later discussion.

While these four classes of curves—circle, ellipses, parabola, hyperbolas—have different names and behave in a sensibly or demonstrably different manner if extended widely, they are not extended widely on a telescope mirror, for we use only the flat parts near the vertex, and there the curves all lie very close together. *These curves (except the circle) give the same pattern of shadows in the knife-edge test* because they are all of a kind, varying only in degree, a fact which we have seen in the gradual transition from one to another, as explained above. This variation is especially small near the vertex, as in telescope mirrors. They all give a "parabolic" type of shadow. Why such a shadow, merely because a parabolic mirror will give it, should be termed *the* parabolic shadow is a mystery, for an ellipse will also give the same appearance, and so will a hyperbola. Except in a general way we cannot distinguish with the eye whether the shadow we see on the mirror denotes an ellipse, the parabola or a hyperbola. If the ellipse were an extreme one near the circle (sphere), and if the hyperbola were also extreme in the opposite direction, these might perhaps be distinguishable by their different depths of shade, but not quantitatively. Actually measuring the radii of the zones is therefore the only way to know which curve we have on a mirror. Even if we should learn for one mirror how to judge the approximate depth of shadow for the parabola, another mirror having a longer or shorter focal ratio would throw us off the track, for the shadow of

an ellipse on a mirror of short focal ratio may be actually darker than the shadow of a hyperbola on a mirror of long focal ratio. Once more, since there seems to have been some question regarding the matter, it is repeated that the shadows of the ellipses, the parabola and the hyperbolas show no observable difference in *shape, outline and location* on the mirror. They differ only in *degree of illumination,* and this can seldom be judged by the eye.

There is another familiar curve, the oblate spheroid, but this was not included in our family of curves. Mathematicians assert that the oblate curve is not a conic section; this curve is a bastard. However, since our aim is not the study of the conic sections as such, but the study of curves as we find



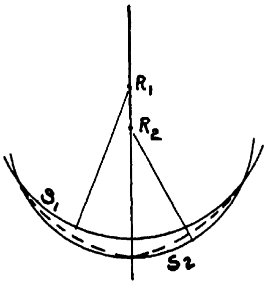
them at times on a mirror, and since the oblate spheroid anyway *can* be found on a cone suitably cut, and often is found on a mirror, we shall not allow this little quibble to worry us. If an ellipse be taken off a cone as described earlier and rotated around its minor axis, as at *f*, we shall have a distorted sphere, like the earth or a round sofa cushion. This is an oblate spheroid. Its radius is longer at the center, and grows shorter toward the ends. Thus it is the opposite of the prolate spheroid, and it gives the opposite kind of shadow. If, instead, the ellipse is rotated around its major axis, as at *g*, we shall have a sphere distorted in the opposite manner, like a football. This is a prolate spheroid. The curve usually designated in mirror making merely as an "ellipse" or "ellipsoid" is the same as the prolate spheroid. The oblate spheroid is also derivable from an ellipse, and the two mirror curves, indicated on one ellipse, are shown in *h*. There is no equivalent term to designate the simple two-dimensional curves corresponding to the oblate spheroid, and in general, the inconsistent, unsystematic, slovenly nomenclature for the whole mess of curves, both two-dimensional and three-dimensional, is perhaps as serious an obstacle to acquiring an understanding of them as their own intrinsic differences. To be consistent we should call the sphere a circloid. It would also help if the suffix "oid" were to mean either the solid figure obtained by rotating a two-dimensional figure, or a deformed solid figure (*e.g.* spheroid), but not both, as it actually does. However, after a time the various significances of the loose nomenclature "soak in," despite the initial difficulty, but they must be learned arbitrarily if learned at all.

After reading all of these attempted elucidations and pondering them well, the worker may turn up with the following question: "If there is only one shape of parabola, and if a mirror is parabolized to a 75 or 80 per cent or some other fractional correction, what shape is it then?" Such a mirror is not a paraboloid but sensibly an ellipsoid!

A point in connection with the curves of mirrors which has evidently kept some well-meaning mathematicians lying awake nights worrying about the blunders which the poor benighted mirror maker may commit is contained in the following typical conversation:

"How," asks the mathematician, "dare you mirror makers tell us geometers, that your method of parabolizing is to *deepen* the central parts of a sphere? As your own sketches show, and as any geometer knows, the parabola is *back* of the sphere, hence you must not deepen your sphere but make it shallower, in order to alter it to a paraboloid." "Well," replies the practical mirror maker, "I am no geometer, but I can make good parabolas, and that is exactly how I do it."

In order if possible to alleviate the headaches which this scandal appears to have caused some of the pure or arm-chair mathematicians (few of whom, for some reason, ever actually make a mirror) it may be revealed that the bare conventional statement that we convert a sphere into a paraboloid by deepening the center of that sphere conceals another truth, and is thus in a sense a loose manner of speaking. As John H. Hindle patly explains it, we



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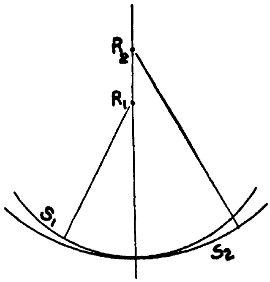


II

"do not deepen *that* sphere into *that* paraboloid." Refer to Sketch I, where $S1$ is the sphere before we parabolize and $R1$ is its radius. $R2$ is the radius of a new and imaginary sphere of reference, $S2$. (Of course, we never actually make this sphere on the mirror.) The parabola fits between the two, touching the new sphere at the center. *It is the parabola which belongs to a smaller family.* In this process the radius of the mirror, and hence its focal length, is very slightly shortened.

"Ah, I see it now," says the mathematician, "but why in the name of

common sense don't you simply wear away the outsides of your sphere, instead of the central parts, and thus obtain the paraboloid which belongs with its own family, avoiding the complication of new and imaginary reference spheres?" Also, the geometer asserts, this method would be more in accord with the beautiful esthetics of geometry. This would be the method

Dr. George Willis Ritchey with 40-inch mirror, U. S. Naval Observatory, Washington, D. C., 1932.

in Sketch II, where *R*1 is the radius of the initial spherical surface. With a lap trimmed just the opposite of the conventional parabolizing lap the outside zones would be worn down more than the center. When the knife-edge test shows that the curve has reached the parabola a new sphere of reference, *S*2, may in imagination be drawn in, touching that parabola at the center and at both edges. The radius of the mirror will now have lengthened slightly, as at *R*2, Sketch II, instead of shortening as in Sketch I. (In both sketches the radius, *R*1, has the same length.) This method, while more direct and logical, is seldom used, because of the practical difficulty of producing the desired curve right up to the edge without turning the edge.

A third method involves parts of the two just described. The parabola is conceived as lying partly within and partly without the sphere of reference, and is obtained by local abrasion, some from the outer edge and some from the center. Commenting on this last statement, John H. Hindle says, "If one is parabolizing a large, heavy mirror which must be supported face upward, it is practically advantageous to use a combination method, deepening the center by using a part-sized trimmed polisher with moderately long stroke, and reducing the outer zones by means of a full-sized polisher trimmed on the outer edge, again with a moderately long stroke. This produces a perfectly blended surface free from rings, which are usually due to short stroke."

The last-named method involves the removal of much less glass than the other two methods (which remove equal amounts) but is even more difficult than method II; in fact, this is a fine method for all except advanced workers to leave alone. In any case, in parabolizing a mirror our chief concern is not the small labor expended on removing the trifling amounts of glass involved, or even the esthetics of geometry, but the most practical method of doing the work and doing it well. Ritchey says, "Parabolizing is done by shortening the radii of curvature of all the *inner* zones of a mirror, leaving the outermost zone unchanged. This is a far better and easier method in practice than to leave the central parts unchanged, and to lengthen the radii of curvature of all the outer zones."

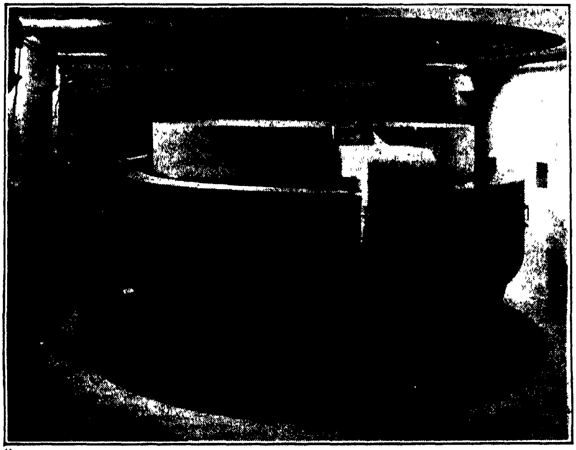
The discussion of the same methods of parabolizing, developed in less elementary manner, may be seen in the *Journal of the Royal Astronomical Society of Canada,* January, 1930, pages 20–24.

Once a mirror is finished we may, of course, cease to worry about theoretical reference spheres and, if we wish, we may regard the mirror, under changing temperature, as changing in the same family of curves. Doubtless, however, in different mirrors these changes occur in part near the edge and in part on the central points; perhaps both in the same direction but at different rates; perhaps in opposite directions in the case of some mirrors, pivoting, as it were, on one zone. A familiar case is when a disk is taken off the lap and the radii of its zones are measured and marked. After 15 or 20 minutes its central zone will have lengthened in radius but its edge will have lengthened in radius still more. Not all disks behave in this manner.

Instructions for Silvering Glass, with a Combined Commentary and Digest of Outstanding Literature on Silvering: Ever since the first edition of the present book appeared in 1926 there has been a persistent call for more detailed instructions for silvering mirrors. Apparently this phase of the amateur telescope making art has proved more difficult for the average worker than any other. The instructions which follow therefore include as much, not as little, information as seems likely in any way to throw light on the silvering process for astronomical mirrors. Some who are old hands at silvering appear to believe that only a part of this process can be imparted through the written word, or acquired except through considerable experience. While there may be an irreducible minimum of this kind, it is confidently

believed that this may be reduced to smaller terms than before, simply by stating, along with the bare working instructions, some of the whys and wherefores of silvering and more of the homely details of the actual process. It should almost be possible, with some understanding of the process and with painstaking in performing it, for the beginner to do good silvering from the very outset. A second excuse for knowing the whys is the fact that it is seldom possible to follow the exact letter of any instructions, owing to special circumstances which usually arise. In such cases the worker who has insight into their real significance may deviate with intelligence; otherwise he must deviate with unintelligence.

The following instructions consist of several "ingredients" woven into a sequence which marches through the various parts of the process either with or without detours, as the reader chooses. If he reads only the parts in



Courtesy Mount Wilson Observatory

When the 100-inch mirror is to be resilvered, a manhole directly beneath the telescope is opened and a giant screw with fork at top rises through the floor, takes the unbolted mirror and lowers it to the silvering room below. A band is placed around it, in which there is a discharge sluice and gate. Four of the dozen men engaged prepare the solutions and, when these are poured on, the mirror is rocked in its trunnions.

italics, jumping over all the others, he will have the bare instructions for the active part of the process. The "detours," printed in ordinary type, may be taken or left, as he pleases. Some of them are intended to throw additional light on the various stages of the process for the puzzled beginner. Others are addressed mainly to the more experienced worker and may well be ignored by the same beginner; such parts are specifically indicated. One

hint may be suggested: The novice should consider whether it is not best on at least the first occasion to silver by one of the most common, simple methods. He may then "go bolshevik," if at all, on subsequent silverings.

Whoever will take the trouble to make a comparative study of the outstanding literature on silvering, beginning many decades back, will be likely to meet with a surprise concerning the wide discrepancy between the different instructions for doing essentially the same thing. Yet these different ways all work—have worked on thousands of occasions. This in itself carries its implications: there is no finality about any instructions for silvering, no right and no wrong way to silver mirrors, except possibly in the eyes of a few who are stuck in a rut. Improvements may and undoubtedly will continue to be made; why not by amateurs? Brashear himself was once an amateur. Another deduction to be made from the variety of published instructions, as well as from experience, is that fine hairsplitting in measuring silvering ingredients will not in itself yield good results. The proportions specified have been varied from time to time, and they vary now from place to place. The processes or reactions are not quantitative—"molecular," as Ellison says—in the familiar chemical sense. If there is failure it can scarcely be attributed to measuring out five percent more caustic or water or reducing solution than these particular instructions call for; though it may conceivably shade the results a bit. A grain off or a grain on—except for ammonia—will not sink you. However, a reasonable exercise of care will pay, even here. But the same attention devoted to meticulous cleanliness which some may characterize as fussy will pay perhaps best of all.

The instructions in Part VI of the present volume, which date back in their real origins many years, have been left in the book. Some will prefer them. The present instructions lean toward the methods used at the Mount Wilson Observatory, but this statement must not be taken as implying that they have the imprimatur of that institution. Valuable help in the form of letters was given by Mr. Ferdinand Ellerman, astronomer in charge of silvering the large mirrors at that observatory. Others, including Dr. Stephen F. Darling of Lawrence College, have helped.

To begin with, the glass surface should be free from pits and scratches. The silver will not cover these up, as the fatigued worker may be excused for fondly hoping, but, if anything, it will render them more conspicuous. They will also diffuse a little light over the field.

Of the three best-known processes for silvering mirrors of optical grade, namely, the Brashear process, the Rochelle salts process and the formaldehyde process, only the first-named will be presented here. The other two are perhaps easier, but one of them, the formaldehyde process, is distinctly inferior in results, giving a darker coat of silver, while only a minority regard the Rochelle salts process as the full equal of the Brashear process. According to Dr. James Weir French, of Barr and Stroud, Glasgow optical manufacturers, the Rochelle salts process gives a reflecting surface "about 5 percent or 6 percent less brilliant than that of the Brashear process. The difference," he states, "can be detected at a single reflection. It is easily

detected after three or four reflections." The National Bureau of Standards states, in flat contradiction to this, that mirrors silvered by the Rochelle salts process show no difference from those silvered by the Brashear process, greater than the error of measurement. However, there must be some good reason why the Brashear process is used on most astronomical reflecting telescopes the world over, including the large ones at the Mount Wilson Observatory and smaller ones as well. For those who wish, however, to use the other two processes they are described in Circular of the Bureau of Standards No. 389, "The Making of Mirrors by the Deposition of Metal on

Master-Sergeant T. J. Stephens of the U. S. Coast Artillery School Detachment at Fort Monroe, Virginia, and a 12-inch telescope mounted on Ford parts. He states that the Ford parts mounting is not steady enough for so large a telescope. Several others have made the same statement.

Glass." This is obtainable only from the Superintendent of Documents, Government Printing Office, Washington, D. C., and is priced five cents (postage stamps offered in payment are not accepted by the Government).

For any mirror between 6 and 10 inches in diameter, assemble in one place the following:

Nitric Acid, one ounce. Try to obtain the most concentrated, with a specific gravity of 1.42. "It will actually oxidize traces of grease which are ordinarily to be found on mirrors. The use of the more dilute, specific gravity 1.22, is quite possibly responsible for many failures in silvering, as it is not an effective cleansing agent."—B. L. Souther, Ph.D., chemist. "Dr. Souther is exactly right—100 percent so. The dilute acid invites failure."—S. H. Sheib, Ph.D., chemist.

Ammonia: C.P., Two or three ounces. Some advise the use of what is called "stronger" ammonia, the strongest commercial concentration, with specific gravity 0.90. According to Dr. S. H. Sheib, "it makes no difference what strength the ammonia has. The reaction is quantitative, and the quantity of ammonia necessarily depends upon the quantity of silver present, and upon nothing else. After the glass stopper of the bottle has been removed a few times, you will no longer have 0.90 specific gravity, due to the escape of NH_3 gas." In other words, the amount of ammonia you use will not depend upon the amount of the liquid. Ammonia is a gas, NH_3, dissolved in water, and if there remains less gas, you will use more of the liquid, determined on a purely empirical basis, as explained later.

Caustic Potash (KOH), C.P., an ounce or two. It generally comes in sticks; if in small pellets, so much the better (easier to divide). Keep tightly corked, as it is thirsty and takes up water from the air. If not available use caustic soda (NaOH) at a ratio of 5/7 as much.

Silver nitrate, C.P. One ounce to be safe, one half ounce to take a chance. Customarily silver nitrate labeled "Chlorine, none," has been recommended for silvering, the more easily available kind marked "Chlorine 0.002 of one percent" being frowned upon from theoretical grounds, since the slightest trace of chlorine is supposed to impair the process. As B. L. Souther points out, the C.P. caustic potash you will probably use already contains 0.01 of one percent chlorine, so there seems to be no need of paying extra for silver nitrate marked "Chlorine, none." He states that he has used that which is marked "Chlorine 0.002 percent" with satisfaction.

Alcohol: Usually used for cleansing the mirror, and in the reducing solution unless dextrose reducer is substituted for the better-known kind. Old recipes, reprinted down through the decades, call for "pure grain alcohol," and for years amateurs and probably most professionals labored under the delusion that this meant what it said, and that this seemingly exacting requirement had some special significance. However, in 1927 several amateurs, with typical disrespect for sacred tradition, tried wood alcohol. This proved successful and so did denatured grain alcohol. M. H. Swenson of Dalhart, Texas, tried lemon extract. That, too, was successful. Still, no one seemed to know just why alcohol—grain, wood, denatured or ex-lemon extract—was needed at all. However, alcohol was called for by the recipe, and apparently that was that. It was used blindly. Dr. Stephen F. Darling of the faculty at Lawrence College, Appleton, Wisconsin, in commenting on such slavish following of a rule, says, "Potatoes were used in making varnish for 100 years and unless a curious experimenter had not proved that the water in potatoes was the only essential ingredient, varnish might still be made with potatoes." In 1931 the Bureau of Standards published the reason for including alcohol in reducing solution—it is used there as a preservative just as it is in other liquids containing organic substances—Peruna, for example. It has no chemical significance in the reducing solution and if that solution is not to be preserved, as is the case when dextrose is used for a reducer, the inclusion of alcohol will be only another case of making varnish with potatoes. Alcorub, Rubcohol, Fabcohol, and possibly other proprietary

rubbing alcohols should suffice to use in the reducing solution. The Bureau of Standards has tried one of these—Alcorub—and found it satisfactory. *An eight ounce bottle should suffice.* If dextrose is to be used as a reducer some other solvent may, if preferred, be substituted for the remaining purpose required of alcohol—as a cleanser of glassware. Acetone is suitable.

Absorbent cotton (anglice, cotton-wool) *a ten-cent package, more or less.*

Distilled water, at least one gallon. When preparing to silver for the first time, a second gallon may be needed. Sold by druggists, garages, 10-cent stores. However, before buying any distilled water your plain tap water may profitably be tested, though relatively few water supplies will

A six-inch reflector with double-yoke mounting, made by Winston Juengst of Tillson, N. Y.

pass this test. Cleanse a glass very thoroughly with alcohol or acetone, rinse it, fill it an inch or so deep with tap water, drop in a crystal of silver nitrate the size of a grain of wheat, and watch closely in good light. If a blue or light pink, cloudy precipitate is seen to be coming off the crystal as it dissolves, the water contains chlorides and distilled water must be used. If no precipitate is seen, out of curiosity add one tiniest grain of table salt and keep close watch for the precipitate. The latter experiment is instructive, as it shows the effect of a minute quantity of salt on the silvering, and why the use of rubber gloves probably will be advisable in order to keep even the tiny amounts of salt in the perspiration of the hands out of the solutions.

Sugar. High grade loaf (Domino type) sugar; or, in a pinch, clean granulated sugar. *Two ounces.* Avoid unnecessary handling.

(Many of the following articles may be found at the 5-and-10 cent store):

Rubber gloves, to keep perspiration out of the solutions and to protect the hands against heavy damage from nitric acid and blackening by silver nitrate.

Medicine dropper, clean. If conveniently available, one marked in minims or drops will be useful.

Chamois skin (anglice wash leather), *a very smooth piece about the size of the hand.* Keep free from the least grit or dust, as it is for burnishing the delicate coat of silver when finished.

Goggles, preferably with well ventilated sides, for if they fog up there will be little opportunity to clear them during the silvering process.

Glass rod or tube for cleaning and stirring, say, six inches long. If not readily available, a clean stick of wood will suffice.

Thermometer, any kind.

Blotter.

Three receptacles for silvering solutions. One should hold about one quart, and should be clear and transparent, preferably 3 to 5 inches in diameter, so that the worker can judge the darkness of the solution in it by looking clear through it. The other two should hold about one pint each. Glass, enameled ware or earthenware receptacles will serve, but those of metal will probably introduce chemical complications.

Measuring glass, either an 8-ounce graduate or have your druggist measure the capacity of a drinking glass or a glass candy jar and then estimate its fractions. Accuracy within about 5 per cent should suffice in the average case.

A small balance will be useful if available but, if not, your druggist doubtless will apportion the ingredients.

Silvering tray of glass, earthenware or enameled ware. If an enameled ware pan is used examine it closely to see that there are no spots where the metal is not covered. The tray should preferably be half an inch to an inch greater in diameter at the bottom than the mirror and deep enough to submerge it, with two inches or more extra in order to prevent slopping over as the dish is rocked back and forth. In a letter, Ferdinand Ellerman, astronomer at Mount Wilson Observatory, who also has the direction of silvering the large mirrors there, says: "My suggestion would be to begin by making a silvering tray for mirrors up to 10 or 12 inches by sawing out a disk of soft pine wood at least one inch thick, and about an inch larger than the mirror. Tack on it about four bosses one-eighth inch thick for the glass to rest on, then nail a heavy pasteboard band around the edge about 2½ inches higher than the thickness of the glass. Let it lap over about 3 inches, and sew the upper edges together. Impregnate wood and band thoroughly with paraffine. In this kind of tray there is no waste space to be allowed for in figuring the chemicals to be used." When impregnating wood with melted paraffine the wood and the brush should first be warmed in the oven. A metal pan may also be coated with paraffine and used for silvering, but if

paraffine is used at all, pains must be taken to prevent any of it from actually touching the glass after it is cleansed, as this will result in unsilvered areas.

Storage bottle for reducing solution (unless dextrose reducer is to be used, as mentioned later) to hold at least two quarts. To be clean.

Reducing solution: This should preferably be made two weeks or a month in advance, so that it may age properly. *Wash the storage bottle inside with soap and water, rinse with distilled water and shake, ending with a little alcohol or acetone. Pour in 20 ounces of distilled water, add one eighth ounce of nitric acid, 2 ounces of sugar, $3\frac{1}{2}$ ounces of alcohol.* Ellerman and Babcock give for reducing solution: Distilled water 25 oz.; alcohol 8 oz.; sugar $2\frac{1}{2}$ oz.; nitric acid $\frac{1}{8}$ oz., and from this and numerous other recipes it may be seen that the proportions given may vary quite widely, and that recipes which do vary are not necessarily erroneous. The amounts of reducing solution made from these ingredients will silver several mirrors, but it improves with age and, as the ingredients are inexpensive, that amount may profitably be made. The portion not used may be stored. Reducing solution "keeps indefinitely, but increases in vigor and rapidity of action when its age reaches several years."—Ellerman and Babcock in "The Making of Reflecting Surfaces," 1920. It is known that the solution is best after six months. In place of natural aging it may be aged at once by heating it up, letting it simmer, but not quite actually boil, for ten minutes. In that case the alcohol should be omitted until after it has cooled.

Weights and measures: Silver nitrate, caustic soda, and other solid ingredients used in silvering, are weighed in ounces which contain 480 grains. Druggists divide this kind of ounce into 8 drams, each dram into 3 scruples, each scruple into 20 grains. This is "Apothecaries' Weight." Ammonia, nitric acid, water and other liquids used, are weighed in ounces which contain 456 grains (in the United Kingdom $437\frac{1}{2}$ grains). This is "Apothecaries' Liquid Measure." A grain is a grain, in either system. Troy weight, a third variety of "headache," will fortunately not be involved in silvering. The specific gravity of silver nitrate is 4.35. For converting metric and U. S. weights and measures: 1 gram = 15.43 grains; cc/29.57 = fluid ounces.

The function of the acid in the reducing solution is to transform the sugar into invert sugar. This is a mixture of equal parts of dextrose (glucose), and levulose (fructose). "Pure dextrose, now available from most pharmacists, has been used with success in place of the cane sugar and nitric acid, and has the advantage that the reducing solution can be used immediately." —Stephen F. Darling in the 1928 edition of the present work. E. H. Barry of New York uses dextrose, or precipitated glucose, which is the chemical equivalent of dextrose, at the empirical ratio of 40 percent; that is, 40 parts dextrose (by weight) to each 100 parts of silver nitrate. Prof. H. L. Johnston of Ohio State University uses it at 100 percent ratio. When the older type of reducing solution is used, the ratio is usually about 50 percent, though at different periods different workers have used various ratios. In the present instructions a 55 percent ratio of sugar-in-reducing-solution to silver

nitrate will be recommended, following the practice at Mount Wilson Observatory.

If dextrose (or glucose, which is a dextrose) is used the nitric acid, for reasons explained above, will be superfluous; and since there will no longer be any need for aging the solution, the alcohol preservative will be equally superfluous. The simple remaining solution may be mixed at once whenever needed and any excess left over need not be preserved. Squibb's or other good grades of dextrose may be had from or through your druggist in one pound cartons marked "U.S.P.," for about one dollar. If available, precipitated glucose may be substituted.

Dextrose (glucose) was used by Common in 1882, but its use appears to have lapsed. It may require several years of accumulated experience on the part of various experimenters working under different circumstances to evolve optimum specifications for the use of dextrose, though it apparently works well without difficulty. In the meanwhile beginners may possibly be better advised if they use the old and reliable type of reducing solution, at the expense of some added pains. More experienced workers are urged to experiment freely with dextrose and report the results, with the surrounding circumstances, in order that a mass of practical data may be accumulated for future use.

Wear old clothes for silvering, as the stains remain.

Put on rubber gloves, wash them with soap and water and then rinse them off with a little alcohol or acetone. Cleanse, first ordinarily, then extraordinarily, all the receptacles and surfaces which will come into contact with the solutions. By ordinary cleansing is meant only what an exacting housekeeper would regard as a perfect job. This, however, will not do here at all, especially in the case of the mirror. An extraordinary or chemical degree of cleansing requires the removal of adhering layers of foreign matter only a few molecules deep which cling rather persistently even after a 32nd Degree housekeeping enthusiast would have done her utmost at cleansing. Alcohol or acetone will give ordinary cleanliness, but it takes nitric acid, elbow grease and persistence to attain the extraordinary kind. **Failure to sense fully the high degree of cleanliness demanded in silvering probably accounts for the majority of unsuccessful attempts among beginners.** *After a scrubbing with soap and water, followed by alcohol or acetone, dilute a little nitric acid with an equal amount of water and go all over the receptacles, etc., again. Rinse with distilled water.* Nitric acid does not attack rubber gloves but without them it stains the hands badly. "All of the vessels, graduates, etc., used for mixing the silvering solutions, must be thoroughly washed, first with nitric acid, then with caustic potash, and rinsed with distilled water, just as the mirror is cleaned."—Ritchey. The Bureau of Standards also recommends cleaning the receptacles with nitric acid or potassium bichromate solution, rinsing with tap water, and finally with distilled water, to remove all traces of acid. Possibly these are unnecessary frills, possibly not. It is important that the chemicals used for cleansing be completely removed, hence

the various washings recommended. *Pour about one half pint of distilled water into the cleansed silvering tray and set it aside.*

Cleanse the mirror, first scrubbing it all over with alcohol or acetone and a gob of absorbent cotton. It is better not to use gasoline for this purpose, as the oil film which this kind of solvent leaves is difficult to remove, even with nitric acid. *Wrap a bunch of clean absorbent cotton around the end of the glass rod or stick, covering up the end so thickly that it cannot possibly work through under strong continued pressure and scratch the mirror, and tie this on snugly. Keep the rubber gloves on to protect the hands and go all over the front of the disk with this swab, as well as partly down the sides. Work systematically and use considerable pressure, covering all parts of the face of the mirror in all directions. Give particular attention to the edge zone, else the silver coat will turn out mangy there. This may require as much as five minutes of swabbing. Do not allow any part of the front to become even temporarily dry during this process. Keep the hands entirely off the face of the glass.* (Need it be said that it is the front of the disk—the concave side—which is to be silvered? However, if the disk is taken to a professional looking glass mirror silverer he will probably silver the back, in spite of all orders, and give the silver a coat of nice green paint into the bargain. This has happened on numerous occasions. Stand over him with a club.) *"If the cleaning has been properly done, the surface after rinsing should not shed water as does a greasy surface, but should be able to retain a film of water over the entire surface when slightly inclined."*—Curtis.

"In commercial silvering many manipulators follow the cleaning with nitric acid by a vigorous swabbing with a saturated solution of stannous chloride ($SnCl_2$) which is carefully rinsed off with warm water."—Prof. F. L. O. Wadsworth. "An important aid in obtaining a firm adherent film on glass has been found to result from a preliminary treatment of the glass surface with chloride of tin. This solution is washed over the glass, or the glass is allowed to stand in it for a half minute or more. The glass is then well rinsed with water and the silvering solution applied. If the glass is not well washed the silvering becomes streaked with reddish-brown markings wherever the tin remains in excess. Just how the chloride acts to produce a better coating is still open to satisfactory explanation."—Donald E. Sharp in "The Glass Industry," December, 1930. Sharp mentions a concentration of 1 part in 1500. Remember, this is a chloride and remove all of it. "The stannous chloride treatment appears to affect the brilliancy of the Brashear coat more than that of the Rochelle salt coat. But it has the distinct advantage of producing a more adherent layer."—James Weir French in "The Making of Reflecting Surfaces." "The application of stannous chloride is not necessary for the production of good mirrors. However, its use favors the production of a heavy deposit under conditions which would otherwise yield a thin, unsatisfactory film,"—Bureau of Standards in "Circular 389." "After cleaning with nitric acid, many advise following with a second swabbing with a solution of caustic potash, followed in turn with an application

of French chalk. I have secured better results with the nitric acid alone." —Curtis. French chalk is old-fashioned blackboard crayon, which is talc, not chalk proper. "It has been recommended that the nitric acid be followed with a swabbing of caustic potash. Our experience is against this, the nitric acid being more readily removed than the potash."—Davidson. "Wash the surface with a 10 percent solution of potassium hydroxide."—Old instructions from Mt. Wilson Optical Shop. All of these special after-treatments are cited, not for the average beginner to worry about, since thousands of mirrors have been silvered without them, but because some of them may prove worth while perhaps on a larger mirror where the worker may wish to go to every length in order to get a few percent added reflectivity. As will be evident, the authorities are not in full agreement concerning some of them. *Rinse the cleansed mirror with tap water, assisted by a tuft of absorbent cotton, and then rinse with distilled water poured on and tipped off, in order to get rid of all of the acid.* Some add distilled water and swab again. Others swab with a drop or two of ammonia, in order to kill the remaining acid. According to Darling, the trace of acid left will do no harm, because the reducing solution is alkaline. *Without letting any part of the surface become dry* (this is important since, for some unknown reason, the coat will not be sure to "take" if the surface has become even momentarily dry) *immerse the disk, face up, in the silvering receptacle and add enough distilled water barely to submerge it.* "We use an amount of water so that there is about three eighths inch depth of solution over the glass."—Ellerman. This refers, of course, to the final depth after the reducing solution and silvering solution have been added. It is not an essential but is one of the many little things that are worth while if one is seeking to obtain maximum results. Otherwise, anything between that depth and an inch or more will give results. In the case of a 10-inch mirror in an 11-inch tray the mixed silvering-reducing solution, equaling about 20 ounces, will just about suffice to raise the liquid level to the desired three eighths of an inch; while in the case of smaller mirrors it will be raised higher. But this will matter little, because there will be so much silver for these sizes in the quantity of silver nitrate to be recommended later. The mirror and solutions should be at the same temperature, but this will usually take care of itself due to the time consumed in preparation. *Set aside 3½ ounces of reducing solution* (the first of the two kinds specified earlier). As stated previously, this corresponds to a ratio of sugar to silver nitrate of about 55 percent by weight. Various rules call for various ratios of sugar-in-reducing solution to silver nitrate, the commonest being sugar-in-reducing solution equal to one half weight of silver nitrate used. The 55 percent rule is the latest result of painstaking experiments conducted at Mount Wilson. "Too much reducing solution gives a black, dirty coat."—Curtis. If dextrose is to be used allow on about a 40 percent basis (40 parts dextrose for each 100 parts silver nitrate crystals, by weight).

In silvering a large mirror the disk, with the help of a retaining wall directly attached to it, may be used as its own silvering receptacle. This method has been used on small mirrors as well. "Wrap a paraffined paper

band around the mirror, tying it on tightly with stout string and allowing it to extend above the surface to be silvered from 2 to 4 inches for mirrors from 10 to 20 inches in diameter. Use heavy drawing or wrapping paper which has been drawn through a bath of hot paraffine so that it has a heavy but smooth coat of paraffine free from runs. It is well to tear the paper at the edges so that it tapers off and does not leave an opening where the overlapping occurs. It is also well to seal it all the way to the top at the overlapping edge by melting the paraffine together with a hot iron."—Old instructions from Mount Wilson Optical Shop. Beware of getting any paraffine on the face of the cleansed mirror. A somewhat similar method was hit on by John C. Lee of Wellesley, Mass., and A. Wade of Los Angeles. A collar made from an old inner tube, the ends scarfed, is tightly tied close to the bottom edge of the disk, so that the bulge of the rubber will permit the solution to reach the extreme edges of the glass. This rubber dam may be tied on before final cleansing of the disk, as nitric acid will not attack rubber, and kept turned down during that part of the work.

Make up the silvering solutions. Continue to wear rubber gloves until the mirror has been silvered. It is better to wait for a cool day to do the silvering, but if this is inconvenient the solutions may be cooled artificially, by means of ice in a surrounding container, as Brashear sometimes did. Solutions and mirror should be at the same temperature in the Brashear process. Ellerman recommends a temperature of 60° or 65° Fahrenheit and states that if the temperature is too high the deposit will be too thin and delicate; if too cold it will be thin and granular, the extreme limits being 45° and 75° (Ellerman). Prof. F. L. O. Wadsworth said that, if the temperature is much lower than 70°F., the film will be too thin; if much higher, too soft. Dr. C. R. Davidson of the Royal Observatory of Greenwich states that "a temperature of 65–70° is recommended as giving the best results. We have to be content with a temperature not much above 55°," he says, "and the proportion of reducing solution has to be increased to suit the occasion. If the temperature is too high, reduction will be too rapid, and the resulting film soft, whilst if too low action is very slow and the film too thin." Likewise Donald E. Sharp says that "generally, the warmer the solution the heavier and softer the deposit will be." When it is actually desired to produce a thin or half-silvered mirror, which will transmit half of the incident light and reflect the remaining half, the silvering is often purposely done at a rather low temperature. Thus not all are exactly agreed as to the best temperature for silvering mirrors, but they are substantially agreed on about 65°. "A rise in temperature from that which is specified will cause the silver to precipitate more rapidly, until a point is reached where the silver would deposit in a spongy mass varying in color from gray to black, depending on the conditions of temperature and concentration."—Darling. A second important reason for temperature control is the liability of explosion if the chemicals are too warm. This will be discussed later.

Workers in the tropics, or where convenient cool spells do not occasionally come, may be forced to resort to some other method of silvering than the

Brashear process, even if that method gives a coat slightly inferior in reflectivity or in other qualities.

From Ceylon in the tropics comes the following communication, written by F. O'B. Ellison, amateur astronomer and a brother of Rev. Wm. F. A. Ellison: "I am afraid some of the silvering methods recommended in 'A.T.M.' are not much use here. It is little use trying Brashear's method, with temperature not to be more than 70°F., when the air and water temperature is always about 86°. Also, on mixing Brashear's solutions here all the silver is precipitated instantaneously. I use Martin's method." This method, as stated by Curtis in the "Publications of the Astronomical Society of the Pacific," Vol. 23, pages 13–32 (same article in "Popular Astronomy," June–July and Aug.–Sept., 1911) is as follows:

"I. 175 grains (11.34 g.) silver nitrate and 10 oz. (300 cc.) water.

"II. 262 grains (16.98 g.) nitrate of ammonia and 10 oz. (300 cc.) water.

"III. 1 oz. (31 g.) caustic potash and 10 oz. (300 cc.) water.

"IV. Dissolve ½ oz. (15.55 g.) sugar candy in 5 oz. (150 cc.) water; add 52 grains (3.37 g.) tartaric acid; boil for ten minutes; when cool, add 1 oz. (30 cc.) alcohol; make up mixture to 10 oz. (300 cc.) in winter and to 12 oz. (360 cc.) in summer. Mix equal parts of I and II; mix equal parts of III and IV in another vessel; combine when ready to silver; immediately on changing color immerse the mirror." F. O'B. Ellison states that clear coarse sugar obtained from local grocers in Ceylon proved satisfactory in place of the "sugar candy" mentioned above. (The instructions just given were written in sugar candy days, many years ago, when table sugar was not the high-grade product it is today, while sugar candy was purer.)

For a mirror of any size between 6 and 10 inches in diameter place one half ounce of silver nitrate crystals ($AgNO_3$) in the largest of the three receptacles—the one of transparent glass. As the ratio of surface areas between a 10-inch mirror and a 6-inch mirror is about as 3 is to 1, the single quantity of silver nitrate and other chemicals recommended for all these widely different diameters may seem puzzling. The one-half ounce of silver recommended is not too little for a 10-inch mirror; it is the amount Brashear used for that size. It is also in agreement with the rule given by Ellerman, namely, 2 to 2½ grains of silver nitrate per square inch of surface to be silvered, for a good, thick coat. On the 60-inch mirror at Mount Wilson 2 grains per square inch are used; on the 100-inch mirror, 2.9 grains, the increase in the latter case being because of the large amount of water in the deep concavity, nearly 2 inches, in that mirror. However, the smaller the mirror the larger the tray it is usually silvered in, relative to the area of the mirror; also, the smaller the mirror the less familiar with silvering process the worker is, in the average case. The half ounce of silver nitrate recommended for 6 to 10-inch mirrors therefore provides an excess of silver for the smaller sizes, and this will tend to favor the beginner. The same quantity—⅝ ounce, in fact—was recommended for 6-inch mirrors in the previous editions of the present work—the same instructions which are retained in the present edition (Part VI), and thus that amount has already been used on

six-inch mirrors by thousands of workers. No quantities are given here for mirrors larger than 10 inches in diameter. Let the case-hardened amateur who has reached that level calculate his own ingredients from the rule, or increase the ratios if skeptical—it helps the chemical trade. *Add 8 ounces of distilled water, which will dissolve the silver nitrate crystals in a minute or two if shaken. Call this Step 1.* The ratio of chemicals to water will be found to vary quite widely between different instructions as given at different periods by various authorities. Ellerman states that "the more concentrated the solution is, up to a certain point, the thicker the coat." Only the experimenter need worry about these matters, however. *Pour about one sixth of this solution into one of the small receptacles and call it the "reserve solution." Set this aside.*

In the other small receptacle place one third ounce (8 scruples) of caustic potash (KOH). The instructions in Part VI call for half as much weight of caustic potash as silver nitrate, while here two-thirds as much is specified. Starting with the original Brashear formula published by Brashear in "English Mechanics," Vol. 31 (1880), page 327, we have silver nitrate and caustic recommended in equal amounts; in 1895 Prof. F. L. O. Wadsworth gives caustic 50 percent of silver nitrate; the same proportion is specified by Curtis (1911) and by the Bureau of Standards in "LC 32" (as in Part VI which was made up partly from the Curtis article of 1911); in 1904 Ritchey, after experimenting, advised two-thirds as much caustic as silver nitrate, and at Mt. Wilson this is still found to be best. "The reason we use the 3 to 2 ratio is because we find we get better results. I would advise retaining this ratio for all sizes of mirrors."—Ellerman, in letter. *Add 8 ounces of distilled water, which will dissolve the caustic potash in a minute or two. Call this the "caustic solution." Step 2.*

To the plain silver nitrate solution add, first off, about 2½ teaspoonfuls of ammonia, a safe amount for the strongest, concentrated variety. This will immediately turn the solution brown with precipitated silver oxide, Ag_2O. Now begin adding more ammonia from the medicine dropper, in increments of about 20 drops—about 1/5 teaspoonful—and stirring briskly for a full quarter minute (important) after each increment. Begin watching closely for first signs of clearing up. A good warning will be the increasing visibility of the stirring rod inside the glass: when ammonia is first being added the rod must be held close against the inside of the glass before it can be seen at all, but when the clear-up is approaching it will become visible farther and farther away from the glass. If it approaches, stir some more and then reduce the increments to 10 or even 5 drops each, and feel your way more cautiously. After each addition at this stage stir like Hell for 30 seconds and then wait a full minute. Otherwise more ammonia will be added before the last increment has been thoroughly mixed and exhausted in dissolving precipitate and an excess of ammonia will turn up as an embarrassment a minute or more later on. What we are trying to do is to add precisely enough ammonia to produce a certain effect, the clearing, and no more. But ammonia, despite labels on bottles, differs quite widely in strength, especially if it is not new, so we cannot tell in advance how much will be needed. If the ammonia was weak to

start with, or old, it may require double the above amounts, or even more. At the last part of this tapering off process ("titration") even a single drop will make a big difference in clarity—especially after stirring and waiting. **Wholly ignore the host of tiny specks in the solution. These give it, as a whole, a dull grayish cast of color. But the liquid between them should now be clear when examined closely. Trying to dissolve these specks will inevitably give an overdose of ammonia, and this will inevitably prevent any coat of silver from forming on the glass.** The precipitate caused by the first additions of ammonia has now been dissolved by the addition of more ammonia (to form $Ag(NH_3)_2NO_3$—Darling). *The plain silver nitrate solution has become "silver nitrate-ammoniacal solution" (Step 3), but it is best now to "back-titrate" a little by adding, 5 drops or so at a time from the reserve solution (stir and wait!) till the solution, between the specks, is slightly cloudy.* ("Until newsprint can no longer be read through the solution, with the flat-bottom tumbler or beaker resting on the paper."—Sheib.) This gives an excess of silver (harmless—merely wasting a copper's worth of silver nitrate), which insures that there will at least be no excess of ammonia (fatal).

The chief source of failure in silvering, after a lack of chemical cleanliness, is the hasty or careless addition of too much ammonia, which will entirely prevent the formation of a coat of silver. Stirring well each time ammonia is added is most important. It takes a lot of shuffling to mix the molecules of two solutions on a real molecule-for-molecule basis. If, however, an excess of ammonia exists (which will not reveal itself by any appearance) the reserve solution to be used later may be sufficient to offset it. The titration process may profitably be tried first on a fraction—say one third—of the silver nitrate solution, as the experiment will give a clear idea of the appearances to expect. The same portion may then be returned to the main part of the solution and the latter again titrated as a whole, and thus it will not be sacrificed. Incidentally, if anyone who possesses the necessary patience and motive will sacrifice an hour or two and a half ounce of silver nitrate, etc., dividing that amount into, say, four parts and pro-rating everything else, and will go that many times through the whole process of silvering from start to finish, silvering four small pieces of glass, he will no longer feel himself to be a tyro or be one. The psychology chiefly involved here is something like this: Many, when silvering their mirror for the first time, find the details confusing and obtain only a mediocre coat. Then, for fear that they will never again succeed in getting any coat at all, they put up for months with this mediocre mirror.

"Potassium hydroxide in the calculated amount is next added, again causing the black silver oxide to precipitate, and it is brought into solution once more by the addition of more ammonia."—Darling. "If the silver nitrate solution has too much ammonia it will not reduce at all, but if it has too little the reduction will take place very rapidly. The KOH regulates this. See Kohlschütter, 'Uber Bildungsformen des Silbers,' in 'Annalen der Chemie,' Vol. 387 (1912)."—Darling.

[1] *The Bureau of Standards recommends that goggles be put on at this point. Pour the caustic solution of potassium hydroxide very slowly into the silver-nitrate-ammoniacal solution just made, never conversely. Stir vigorously all the time. Step 4.* "Your Step 4 is a very important step. Especial emphasis should be made that the caustic solution be added **very slowly** and **stirred vigorously** to prevent the formation of silver fulminate. A little may form anyway, but will do no harm. If the novice were to pour the caustic solution right into the silver-nitrate-ammoniacal solution and stir, the goggles might come in handy, as the resultant mixture, with the fulminate which it would form, would be quite likely to blow up. But if my suggestion is followed, no goggles will be necessary and no danger be likely to arise."—Ellerman, in note.

Here we digress to discuss the question of explosions, in order to see it at its worst—which is not very bad, after all, unless one is given to nightmares. It is well, however, to know the size of a risk, else we shall suspect there is more to it than is told, and be unduly apprehensive. "When the solution by evaporation or mistake has become too concentrated, the silver hydroxide-ammonia has a tendency to decompose into ammonia, water and silver amide. From the latter ($AgNH_2$) a part will be decomposed into ammonia and silver nitride. In this way in the solution will be found a mixture of silver amide and silver nitride. This silver oxide-ammoniac is very explosive, as is also the silver nitride, called 'Berthollet's fulminating silver.' Even when the material is wet the slightest touch may cause an explosion. It is therefore clear that this mixture, formed in a concentrated solution as a brown-black flaky sediment, is extremely dangerous. A bottle containing such a solution will explode at the slightest touch, with a force exceeding many other explosive materials. However, the formation of the explosive precipitate is only possible when the solution has exceeded certain limits of concentration. The ammoniacal silver nitrate solution used for silvering purposes must always be very dilute, and the concentration is much below the above-mentioned limits."—Wolf, in "The Glass Industry," Jan. 1932. Wolf, in writing these warnings probably aimed them more at large-scale producers of plate glass mirrors—readers of "The Glass Industry," than at telescope makers. In large plate glass mirror silvering shops where mirrors are silvered every day there is often a temptation to allow familiarity to beget contempt, also to accumulate large quantities of silvering materials, and insurance officials have to deal with the silvering factory risk on a very practical basis. But, Wolf states, the solutions used in silvering mirrors are very dilute and relatively unlikely to explode. However, they must not be allowed to evaporate and thus become concentrated and relatively likely to explode. Wolf says in the same article, "The explosion of silvering solutions is always a consequence of a failure of workmanship." True.

In "Circular 389," the Bureau of Standards states that "one is taking an entirely unnecessary risk, probably greater than is commonly realized, in silvering without goggles . . . compounds may be formed which are violently explosive and which detonate as a result of the slightest mechanical dis-

turbance. At times these explosive compounds have formed with serious consequences during the process of silvering, and instances are recorded in which explosives of this nature have resulted in loss of sight through the action of ammonia on the eyes, or have been sufficiently violent to produce considerable property damage. These explosions seem more likely to occur when using a formula in which potassium hydroxide is one of the constituents of the silvering solution, as in Brashear's method. It seems, however, that they are possible occurrences with any of the methods of silvering. Explosions are very likely to occur if the residue remaining after silvering is allowed to become dry or if empty vessels in which the silvering solution has been prepared or stored are allowed to dry without first having been carefully cleansed. Consequently, all vessels containing silvering solutions should be carefully cleaned immediately after use, and all residues remaining from the silvering should be washed down the sink or otherwise safely disposed of without delay. Bottles containing the silvering solution should be kept tightly corked when not in use, to avoid the possibility of lowering the level by evaporation and the formation of a dried residue on the side walls. It is further recommended that the silvering solution for the Brashear process should not be stored, but prepared only as required. There is no danger associated with the reducing solution. Even after taking all recommended precautions it is considered advisable that the operator should always wear goggles for protecting the eyes when handling the silvering solution."

There are two forms of silver explosive, silver fulminate and fulminating silver. Silver fulminate is C=N–O–Ag, or AgONC. This explodes when wet but, according to Darling, it cannot possibly be formed until the reducing solution has been added. In practice the comparative freedom from explosion arises from the low concentration of the solutions. "Fulminating silver is not so precise a term, according to the Bureau of Standards, but usage appears to favor its restriction to Ag_3N and Ag_2HN. These may be prepared by treating silver nitrate with ammonium hydroxide and potassium hydroxide. This form explodes only on drying, according to some authorities.

E. H. Barry of New York relates that, in order to test the stability of a mixture of silver nitrate, caustic soda and ammonia, it was allowed to stand over the week-end in a closed room, in an open beaker. On Monday morning the contents and the fragments of the beaker were found to have been scattered all over the ceiling. The temperature had reached nearly 100° F. in the room.

In a case described in "The Scientific American," April, 1932, some silvering solution had been preserved for three months. Every piece of glassware in the room was broken by the explosion, which took place at night with no one present.

In another case, related in the same place, 16 ounces of silver-ammonia-hydroxide solution, before the reducing solution had been added, blew up during the night, broke the containing bottle into fragments and blew the shelf on which it rested off the wall. The temperature was high, 85° F., and the solution again had been held over.

In a third case the silver-hydroxide-ammonia solution actually exploded

during the silvering process, possibly because the room temperature was high. Silver fulminate formed on top of the solution, exploded and blew the container into fragments, which lodged in the wall, and the ammonia caused the worker serious eye trouble. He had not worn goggles.

Another incident was described in the "Journal of the American Medical Association," Vol. 94, No. 22, by John Albert Marshall, D.D.S., Ph.D., of San Francisco, as follows: "An explosion occurred . . . which has jeopardized the eyesight of a research worker in one of the laboratories at the University

The shelf in the Howell and Sherburne shops in Pasadena, which was blown off the wall. Marked with a cross and arrow.

of California. Sections of bone and teeth with their contained soft tissues had been stained by the so-called silver nitrate method. The . . . dishes containing the ammoniacal silver oxide solution were inadvertently left standing in the sun from Saturday noon till Tuesday morning. There were traces of alcohol in the silver solutions. . . . The sunlight hastened a chemical reaction between the silver, the ammonia and the alcohol, and there resulted from it a highly explosive, very sensitive and unstable compound, silver fulminate (C=N–O–Ag), to be distinguished from the so-called fulminating silver, which explodes on drying. When the dish was taken up to be emptied it was warm from the sun. The mere movement of the liquid was responsible for the detonation. . . ."

The Bureau of Standards, in a letter, states that silver fulminate can be

prepared by treating silver nitrate with an excess of nitric acid and ethyl (grain) alcohol.

Another case of an explosion, also a low-grade one, is described in a letter from Mr. Ellerman, who refers as follows to the explosion risk when preparing the silvering solution: "It is the silver fulminate that is formed if the caustic solution is added too quickly and not thoroughly agitated during the process. On one occasion a man assisting me in preparing a batch for the 60-inch mirror, while I had stepped aside for a moment, rapidly poured the caustic solution into the ammoniated silver solution. When I learned of this I remarked that we were probably in for trouble. The solution remained black, even after adding more than double the usual quantity of ammonia necessary, when suddenly the jar, containing about 2 gallons of liquid, exploded into our faces, covering us quite thoroughly. Fortunately both of us wore glasses, so our eyes were protected, but our faces were such that we could hardly have appeared in polite society for a few days. The other explosion risk is that of the fulminate forming on the completed silvering bath, and on the used solution left over after silvering. If these are left standing fulminate is formed which floats to the surface and, when a sufficient quantity is formed, it is apt to go off at the slightest touch." "The silver fulminate appears black," Mr. Ellerman adds, "when wet and floating in or on top of the liquid, but has a luster something like that of graphite." He suggests that, in dealing with a dish in which a dangerous solution of fulminating silver has been allowed to dry up, no slightest attempt be made to touch it, but that a heavy blanket or mattress be thrown over it and an attempt then made to explode it by percussion, if the blanket itself does not explode it.

It will be evident that none of the low-grade explosions just described was comparable with the explosion of a like quantity of concentrated high explosive. The effect was usually more of the nature of a haymaker from Jack Dempsey than being blown to atoms by a ton of TNT. At any rate, too much of this kind of warning probably will frighten the average beginner entirely out of his hobby, and his wife, mother or maiden aunt out of her wits if she ever hears about it—which in the interests of common sense she possibly should not! All of the precautions mentioned are fully recommended, but the other side of the picture—which should make the amateur willing to proceed after gaining a proper understanding of the nature of the relatively small risks involved—is that, since 1926 when "The Scientific American" began popularizing the telescope making hobby, several thousands of wholly inexperienced workers have silvered mirrors—probably 10,000 jobs up to 1932—yet only two or three accidental explosions have been recorded among all these amateurs and **in absolutely every case the workers admitted they had kept the solutions standing several hours or longer, or had silvered on a very hot day.**

For a second time ammonia is added to the solution and a careful titration is carried out. This one should require less ammonia than the other. *Begin by adding about 1⅔ teaspoonfuls (say 160 drops), then taper off as before,*

toward the end stirring 30 seconds and waiting 60 after each increment (Sheib), *as the balance, indicated by a clear-up, approaches. Be every bit as careful as before. Ignore the specks and by close inspection watch the solution between them: while this should be just clear, the solution as a whole will appear grayish when held at arm's length.* (These instructions are for the worker who has never before silvered, and to some who may have silvered two or three mirrors they may seem to call for much fussing. Possibly this is true, but it is more likely to be the worker who has silvered two or three times and had good luck, than the one who has silvered many times and had occasional humblings, who will regard slow, careful titrations, as described above, in that light. There are, however, some places where experience will reveal short cuts.) (Very lowly beginners may take comfort if told that self-satisfied old hands setting out blythely to get a fine coat sometimes get nothing.) *It is fully as necessary as before to avoid excess of ammonia. However, most beginners get it, so the reserve solution to the rescue! Back titrate with increments of perhaps a quarter teaspoonful (say a squirt from a medicine dropper), and stir vigorously after each. At first a precipitate, brownish but not dense, will probably form, but will redissolve on stirring. "As soon as the brown precipitate is redissolved slowly, it is well to dilute the remainder of the reserve solution so that the division of the particles formed will be finer, and thus a better 'straw color' is obtained."—Ellerman, in letter. Dilute to about quarter strength with distilled water. Continue adding from the diluted reserve solution. With each increment the yellowish tinge of the solution, after thorough stirring, is slightly darker. The object is to obtain a dark straw color (not straw hat color, which is bleached), sometimes described as a light brown, sometimes the color of weak tea. It is better dark than light.* The whole object in this second titration is to bring the solution to a chemical balance, and then, by adding reserve solution, to tip it toward an excess of silver; so that, when the reducing solution is later added, the silver in metallic form will be made available. The straw color indicates the presence of a little free silver oxide—very desirable. **There is no use of going ahead if this condition is not obtained; that is, if there is an excess of ammonia, for failure will then be certain.** *If, as frequently occurs due to unfamiliarity with the process, the whole remaining amount of the reserve solution fails to produce the straw-colored thin precipitate required, more should be mixed.* This is why purchasing only one-half ounce of silver nitrate is taking a certain chance. (Anyway, silver nitrate keeps well and may be used later.) Drop, say, one-eighth ounce of silver nitrate crystals into about one glass of distilled water and when it has dissolved continue adding from this. *If, on the contrary, the reserve solution has not been entirely used when the straw-colored condition is reached, the remainder may be salvaged by adding to the main solution first a few drops of ammonia and then reserve solution—enough to give the straw color as before—and alternating the two until the reserve solution has all been added. The solution is now ready for reduction. Step 5.* **"Such a solution now contains the original silver nitrate in a form which will give up its silver at the right speed under the influence of the reducing solution at a certain temperature."**

—Darling. At this stage many filter the solution through a generous tuft of cotton placed loosely in the large part of a glass or enameled ware funnel, and into a spare receptacle. Mr. Ellerman comments on this practice as follows: "We do not filter the solution, as we find that the little flakes in it do no harm and the filtering removes some of the silver; it also delays the process." *Pour in the reducing solution, which was previously set aside, and stir the two together* (*Step 6*), *then pour the whole solution immediately on the mirror, and begin gently rocking the tray.* "The chemical reactions involved in the process of silvering can be compared to those which occur in the smelting of an ore to obtain the pure metal. Here the pure silver ore is the silver nitrate uncontaminated with other metals, and the smelting agent is the reducing solution. The reaction consists in the slow deposition of metallic silver from a solution of its salt by means of a chemical known as a reducing agent, the reaction being called reduction by chemists. Among the many reducing agents available are formaldehyde, Rochelle salts, dextrose and fructose. Our reducing agent is cane sugar which, in the presence of a small amount of nitric acid, is converted into dextrose and fructose."—Darling. Fructose or fruit sugar is the same as levulose or laevulose. Reduction is the process of withdrawing oxygen from a compound. Here we draw oxygen away from silver oxide, and silver in metallic form is left. "There are two reasons why cane sugar (beet sugar will serve as well) is chosen for our particular purpose. First it is a weak reducing agent in a sense that the silver is deposited slowly and uniformly; and, secondly, it is one of the commonest, yet one of the purest, substances easily obtained."—Darling. The juice of berries has been used successfully as a reducing agent in silvering.

The liquid will, or should, very soon turn dark, like strong tea, before long reaching a deep, murky, almost inky, shade. "According to Kohlschütter ('Annalen der Chemie,' Vol. 387, page 86 (1912), an exhaustive article) an ammoniacal solution of silver nitrate containing KOH has silver in a form in which it can be reduced by sugar solutions slowly enough to form colloidal silver. Agitation brings more solution into contact with the glass and should be carried out throughout the process; in other words, agitate the solution as soon as it is in contact with the mirror, and keep it up until the mirror is removed."—Darling. *The solution will next change to a brown, —entirely different from its previous color—like coffee with cream, or river flood water; sometimes darker, however. If the tray is tipped, bringing the mirror near the surface, a thin phantomlike coating of silver may soon be seen on it—perhaps just a speckling at first. Soon the solution will begin to clear a bit, for parts of the mirror will occasionally be glimpsed even without tipping the tray. Still later, if it is tipped, dark specks like coarse black pepper, will be seen lying on the mirror, which by now should appear quite bright with silver. Examine it more closely to make sure that the coat is continuous, even if not yet thick, and if it is continuous, stop rocking the tray and begin swabbing the mirror surface with a handful of absorbent cotton. Swab at first very lightly with just the weight of the wet swab*

trailing behind the hand. Move swab systematically over the whole surface. The purpose is to keep displacing the dark specks, also to agitate the solution. If swabbing is begun too soon, before the coating is continuous, the silver may plow up here and there and these areas will not cover with silver like the others. "One of the important things we find is the proper time to begin swabbing the surface. It is when the silver seems bright and there is quite a deposit of black specks on the coat."—Ellerman letter. *As the coating grows assuredly continuous it will withstand more pressure, but do not press hard even then. By now the uniform appearance of the solution will have broken and on close inspection it will be seen to consist of what is really a translucent and later a transparent liquid, with many light brown flakes or clusters of flakes suspended in it, giving it the general appearance from a distance of two feet or more of being still a uniform brown liquid. This clearing shows that the solution is nearly spent. Even if it is not yet quite exhausted, another threat now enters in—bloom. This is silver in a different state (coarser), which begins insidiously to deposit on the mirror, arriving so gradually and evenly that it may not be discovered at first.* The mirror is produced by the deposit of colloidal silver—the metal in a very fine state of subdivision—on the glass. "This colloidal silver, by a surface reaction, forms a layer on the surfaces and, if colloidal enough, produces mirrors."—Darling. *If bloom begins to form on the coating, remove the mirror, for it is now receiving more harm than good.* "If one waits too long there is likelihood of bloom forming which will be hard to remove."—Ellerman letter. "A difficult point is the decision as to when the process should be stopped. If the solution is thrown off too soon the coat will be thin; if left too long a whitish bleach deposits, and no amount of burnishing will make such a bleached coat as brilliant as one correctly deposited."—Curtis. "The former alternative is preferable."—C. R. Davidson, Royal Observatory of Greenwich.

All of these details to be remembered within a very few minutes of busy action may impress the beginner that silvering is a very complicated process. But if you try to get everything just right on the first occasion you may come out almost a nervous wreck. These exact details are mainly for the worker who wishes to improve on his previous work. If, instead of observing any of them, the worker were merely to dump the mixed solutions on the mirror and walk away for five or ten minutes he still would find some kind of coat—provided he has prepared solutions which will do business at all; probably the coat would be almost half as good as a fine one. However, do not do this, but observe what you can and do what you can, and try to do more the next time you silver.

To recapitulate: In silvering a mirror we—

Dissolve silver nitrate crystals in water, reserving a part............Step 1

Dissolve caustic potash in water and hold in readiness..............Step 2

Add ammonia to the dissolved silver nitrate, causing a precipitate, then add more ammonia to dissolve the same precipitate........Step 3

Add the caustic potash solution to the silver nitrate solution........Step 4

Add ammonia to dissolve the precipitate thus formed, and then use reserve solution to prepare the solution for ready reduction......Step 5

Add the reducing solution..Step 6

Next we silver the mirror, as summarized in the following table, which the beginner may profitably copy in large letters on a card where it will be readily visible during the process, for there will be no time then to look things up in books.

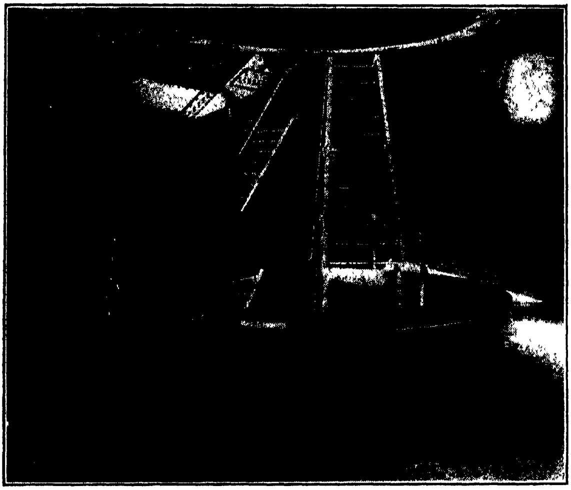
(1) Pour on reducing solution. Begin rocking tray.
(2) Liquid alters to deep murky hue, then gradually becomes lighter.
(3) Tip and inspect disk every quarter minute or so. Continue rocking.
(4) When coat is continuous and black specks are settling on mirror, change to swabbing.
(5) Solution clearing, clusters larger, bloom starting—Quit!

All of this may take place within two minutes, or it may be stretched out over 20 minutes, depending on many factors. Three to eight minutes is closer to average.

Rinse the mirror, preferably in distilled water. Instructions usually state: "Rinse the mirror in tap water, and if there is much gray bloom on it swab vigorously under the running water with absorbent cotton." Darling disagrees with this, stating that all the washing should be done with distilled water, because almost all tap water contains chlorides, and this causes a bad effect on silver. If the coat is good and thick it will withstand rather vigorous scrubbing, though one must not expect the coat to withstand heavy pressure. "Scrub vigorously without vigor," is one pat way it has been expressed—perhaps by Pat.

Stand the mirror on edge to dry. With the corner of a blotter remove water at the edges, not, however, actually touching the mirror. "It is best to cover the coating with 95 percent alcohol in order to arrest oxidation of the moist silver surface. The alcohol can be poured off at once."—Prof. H. L. Johnston of Ohio State University. *Without delay rinse out all of the receptacles with distilled water and put them away upside down in a tight place.* If this is done it will hardly be necessary next time to cleanse them except with distilled water. *Flush the mud in the tray down the sink, to obviate risk of explosion.* Most of this mud is pure silver, being dark for the same reason that the pure silver is dark on an exposed photographic film. "The crystals are so arranged that the light is absorbed by reflection forward and backward."—Bancroft. By far the largest part of the silver is utterly wasted but the failure of the silver to go where it is most wanted cannot be helped. Assuming that the coating on the mirror is 1/250,000-inch thick—a good thick coat—we may easily calculate what part of the metallic silver in the silver nitrate actually deposits on the mirror. It is scarcely one percent; a single grain of silver for a 10-inch mirror! A little silver will be deposited on the tray and a little on the back and sides of the mirror. "Since the reaction to form mirrors takes place only at the surfaces, it is no wonder that very little of the silver actually used is found on the glass. Agitation brings more solution in contact with the glass."—Darling. A swab

dampened with very dilute nitric acid will remove the silver on the back of the glass (and, unless care is exercised, some from the front, also) but it is best to leave it there temporarily for practice in burnishing, estimation of adhesive quality of film, etc., later on.



Courtesy Mount Wilson Observatory

The 100-inch mirror rising from the silvering room after being resilvered.

Should the coat be thick or thin? "A thick coat is better in every way."—Curtis. "So thick as to be nearly opaque, even to the sun's disk."—Ritchey. "The right sort of film is as opaque as a half-crown. If you can see through your film it is not thick enough."—Ellison in "English Mechanics." If thin the percentage of the incident light it reflects will be lowered, but the mirror will not be altogether useless—Ellison does not actually mean that. When held up to the sun it may appear blue. This means that part of the light at the blue-violet end of the spectrum is passing through and therefore that the same light will pass through and be lost when the mirror is in the telescope.

In general, how thick are these films? Very thin. A coating as thick as 1/150,000 inch rates as very thick; one of 1/270,000 inch thickness rates as thick: if less than about 1/500,000 inch thick it rates as thin. A way to measure the thickness is by Nobili's rings, as worked out by Curtis. "Place a very minute crystal of iodine on the silver surface; obviate the effect of air drafts by placing over it a small beaker, which should not however fit

the surface tightly. Count the rings, which will form around the crystal in a few minutes. Then the thickness of film will be:

To first dark ring......................	0.000,018 mm.	
To second bright ring..................	0.000,037 mm.	(thin)
To third bright ring....................	0.000,074 mm.	
To fourth bright ring..................	0.000,110 mm.	(thick)
To fifth bright ring.....................	0.000,147 mm.	
To sixth bright ring....................	0.000,184 mm.	(very thick)
To seventh bright ring..................	0.000,220 mm.	(very thick)

The 0.000,184 mm. coat should just barely permit the sun's disk to be found through it. Needless to say, this experiment will leave a small permanent ring a quarter inch or so in diameter, on the silver coat.

A mirror may also be silvered face down. This method has both advantages and drawbacks. No mud will deposit on the mirror, as mud does not settle uphill. But bloom may. By this method the progress is harder to observe and the disk must be supported suitably in the solution. But the coat will be clean, relative to the other. Large mirrors are nearly always silvered face up, but perhaps some would be silvered face down were they not so big and awkward to support in that position. Years ago Common silvered a 37-inch, 400 pound mirror face down, with the aid of a large suction disk made with great care. Ellison silvers all of his mirrors face down. He recommends the following method, in "The Amateur's Telescope." A block of wood is attached to a cross-piece of wood long enough to span the tray, and this is pitched to the back of the mirror before the latter is cleansed. (A rubber suction disk might be used here.) The face of the mirror should come about one half inch above the bottom of the tray and be level. It will be necessary to make sure that the total bulk of the solutions will be enough to reach and cover the face of the mirror. If not, some of the distilled water may be left in it when the time comes to pour in the silvering solutions, as the Brashear process is not dependent on an exact volume of liquid. "If the Brashear formula is used it is not necessary to pour off the distilled water already in the tray, provided that its volume does not greatly exceed the combined volume of silvering solution used."—"Circular 389," Bureau of Standards. It is most important to see that no air bubbles remain trapped under the concave face of the mirror. Tilting the mirror will permit them to escape. When silvering by this method Ellison determines when the solution is spent, as follows: He keeps a few glass slips handy, carefully cleaned, and inserts the end of one in the solution for a time. If the glass shows no film the solution can deposit no more silver. "There is no harm," Ellison also states, "in lifting the mirror out for inspection. I am aware that this is clean contrary to the lore of the old masters; but, as I have, like Father William, 'done it again and again,' and found no harm resulted, I believe I am safe in recommending it." Here he adds a comment which we heartily second, to wit: "This is not the only 'precept of the elders' which I have had occasion to reject. During a length-

ened course of experimenting I have frequently disobeyed solemn precepts of Draper, Francis, Wassell and others, just to see what would happen. Very often nothing happened. Nothing very terrible ever happened. And a good many quite new improvements resulted."

Double or multiple coating is a modification of the ordinary silvering process which many recommend, though the beginner may dispense with it to possible advantage, as it adds complication to unfamiliar work and is not

A six-inch reflector made by Professor George W. Corner of the Department of Anatomy at the University of Rochester.

essential. The mirrors at Mount Wilson are double coated. Ellison recommends it; so does the Bureau of Standards. It gives as much as 50 percent better coats. One way to double coat is to silver the mirror in the regular manner, using, however, half amounts of everything; then, leaving it in distilled water, for it must not dry for an instant, go all the way back to Step 1, prepare new solutions and give it a second coat. If an attempt is made to split the solutions into halves at some later stage there will be a risk of explosion due to keeping them on hand during the work. Another way is Ellison's: "What we may call the 'installment plan' in silvering," he says, "gives very fine films and requires a minimum of interference with them. It will be found that, if the mirror is removed from the bath before the silver is quite completely deposited, the film will be very brilliant and

require next to no polishing, but it may be thin. Therefore," he adds, "make a solution half or two-thirds strength, and give the mirror a short immersion—*i.e.*, remove it when you judge that the deposit is not quite complete. Put it aside in a dish of water and make up another bath and repeat the immersion, removing the mirror, as before, when not quite complete. Do it a third time, if necessary. This gives a very brilliant film of any required density and no pinholes or air-bubbles." "Pinholing, or obtaining a silver film full of tiny transparent spots, is due to sediment in the solutions or wash water. The source of this is frequently the ammonia water, and it may be remedied by proper filtration of the solutions."—Donald Sharp in "The Glass Industry." An improvement even over these methods of multiple coating, if circumstances permit it to be followed out, has been described by Ellerman in a letter: "In double coating we add the entire amount of reducer to just enough water to cover the surface, mix well and add one half of the silvering solution. When the flakes begin to gather in large clusters we add

A six-inch reflector with Pyrex mirror, made by Prof. M. de K. Thompson of the Department of Electrochemistry, the Massachusetts Institute of Technology.

the second half of the silver solution. This gives the thickest coats. It is better than two separate coatings. The ammoniated silver-caustic solution is divided into two batches and each is brought to straw color with the reserve solution when needed. This adds a little work but prevents silver fulminate from being formed on a solution which is ready to pour on the glass." This method is practicable when an assistant is available to rush

into the breech with the prepared second solution at the psychological moment, but otherwise the long delay while the second batch is being prepared would probably result in a heavy bloom being left on the first coating.

Do not expect to get sure results in silvering, even after much experience. Nobody does. It should, however, be possible to get good results in 80 percent or more of the cases and, if one has a painstaking nature and thinks things out as he goes, that average should be very materially bettered. Sometimes, however, a solution will apparently balk, refusing for some unknown reason to do business. Even old hands meet with this.

To remove silver nitrate stains: Dampen the area involved and rub potassium iodide crystals over it until they dry and fall off. Ordinary stains should be greatly reduced by this method within a few minutes. If not, leave the gummy remaining matter on the skin an hour or so, or rub in some more crystals.

Dentists nowadays silver teeth in order to fill up their porous areas with silver. It was discovered that ammoniacal silver solution penetrates unhealthy tooth tissue, while healthy tissue is non-absorbent. A simple modification of the formaldehyde reduction process is used, and the lower "index of reflectivity" always resulting from this particular process doesn't matter; in fact, the formaldehyde process is just about right—for teeth.

A booklet entitled "A Discussion on the Making of Reflecting Surfaces," published by the Optical Society (London) at 5 shillings, contains a brief historical survey of silvering and a valuable bibliography of the chief references to the literature on that subject. Otherwise the contents are disappointing.

When the mirror is thoroughly dry it should be burnished. "Make two rubbers of best chamois skin, stretched over balls of absorbent cotton. Go over the entire surface in short circular strokes, first with the plain rubber to harden or compact the film. Then grind a little best optical rouge into the chamois of the other rubber and repeat. Dust the mirror frequently during polishing and occasionally run the edge of a knife over the pad to prevent the solid particles of rouge from making scratches. With a perfectly deposited coat only a few touches with the rouged pad will be necessary."—Curtis. It is expedient at first to practice this burnishing process on the back of the mirror, where some silver will be usually found, and thus learn just how much and how little punishment each silver coat will stand. Then hold the mirror to the light and see whether many scratches have been made, perhaps by an imperfect pad, in the back coat, before proceeding too eagerly to the front. Many fine coats have been injured by scratches in the burnishing process. During the burnishing operation avoid dust, as this will get under the rubber and scratch the silver. Do not breathe on the mirror, as dampness is bad for it. "Occasionally we have secured coats that are beautifully bright without burnishing, but even in these cases we have found it desirable to burnish at once, as the life of the coat is thus prolonged."—Curtis.

In Part II, Ch. VII, Ellison tells how to secure unusually fine rouge for polishing the silver coating.

If the coat is good it may be reburnished from time to time. This is done on the 100-inch and 60-inch mirrors about once a week—the resilvering once in about six months. "A good silver film is so hard that it permits perfect reburnishing at least 50 times by those who know how and when."—Ritchey. "Never attempt to get rid of tarnish by re-polishing. You will lose far more light by thinning the film than you will gain by polishing it."—Ellison in Part II, Ch. VII. When experts fall out what is the amateur to do! The following is from a comment written from Pasadena by Russell W. Porter: "Mr. Hitchcock (Dr. Hale's expert mechanician) called my attention to Chapter VII, Part II, in which Ellison refers to there being no gain in trying to re-burnish a tarnished mirror. Mr. Hitchcock says they do it here right along with a rouge pad. They first hold a bunch of absorbent cotton in front of the mirror and see whether its image looks yellow. If it does, they burnish away until the reflection looks white."

If left in the open air, especially where there is a trace of sulphur from coal burning boilers or from illuminating gas, a mirror will tarnish in a few days, though if left exposed in pure air it may not be tarnished badly within several weeks. If properly cared for, even anywhere, it should remain in good condition at the end of a year, but in industrial regions such as Pittsburgh, far less. See Part II, Ch. VII. If the cell has no interfering projections at the front the mirror may be kept from the air when it is not in use simply by inverting it on a piece of glass. This is Russell W. Porter's method. Another way to protect a mirror is to keep on it, when the telescope is not in use, a soft fluffy pad of absorbent cotton a bit larger than the mirror and stitched loosely to a disk of tin or board. This is very effective, though it leaves bits of lint on the coating. A third method is to cover the mirror with a tight cap within which is attached a cloth soaked in a 10 percent solution of lead acetate and dried. It should not touch the mirror. This may be combined with a moisture-absorbing pad of absorbent cotton which is dried out during the times while the telescope is in use (Part II, Ch. VII). A fourth method, as practiced by John C. Lee, is to grind the cover of a crock to a tight joint with Carbo, place in it some calcium chloride which absorbs atmospheric dampness, and keep the mirror out of doors in the crock. Calcium oxide, *i.e.*, unslaked lime, will have practically the same effect. A fifth method is to lacquer the silver coating. This is not a new, untried, "stunt," as some have suspected, but has been used for many years (See Bell, "The Telescope," page 221).

Some workers question whether lacquering causes any optical disability to the mirror, others assert that it does, even if done correctly. For example, Bausch and Lomb say: "For the most precise work the lacquer coating should not be used, for it will cause a slight deterioration of image quality." Likewise the Bureau of Standards, in "Circular 389," says: "This process of protecting front surface mirrors, however, has not been found satisfactory when the best optical surfaces are desired." The use of lacquer on a mirror

was first tried years ago at the Paris Observatory. Bell experimented with it, lacquered the 24-inch reflector at Harvard and it was used there satisfactorily for years. He did not find that the lacquer deteriorated the definition when the coating was put on correctly. Porter used lacquer on a large number of mirrors. Perhaps the chief basis of the objection is esthetic. After one has produced a beautiful coating of silver it is disconcerting to cover it with a broad pink-and-green fringe, however thin and tenuous these colors are. If Lastina lacquer, a trade product, is used the worker is advised to disregard the maker's standard instructions which call for a 2 to 1 dilution with amyl acetate. These instructions are intended for protecting ordinary silverware—knives and forks—and that dilution will give much too thick a coating for a telescope mirror. Dilute the lacquer 10 to 1 or 12 to 1 with amyl acetate (properly, iso-amyl acetate). The ordinary trade equivalent, banana oil, may cause trouble, not being C.P. At the right dilution the lacquer will be practically as thin as water and will drop in separate drops from the end of a stick without any reluctance. Choose a place very free from dust. Hold the mirror in one hand, pour on some of the diluted lacquer (Do not use a brush!), tilt the mirror this way and that until the entire surface has been wet by the lacquer, pour off the excess and stand the mirror on edge at once. Approach a blotter delicately to the excess drops at the bottom, and keep removing the accumulation there. Do not touch the actual mirror with anything. The object is to apply to the silver as thin a coating of lacquer as is humanly possible. Leave the mirror on edge for an hour, in a dust-free place, to dry.

When the lacquer is properly applied, and dry, the surface will be crossed by one or perhaps two bands of inconspicuous color, blue at the top edge, pink at the bottom. These are interference fringes between the rays reflected from the top of the lacquer coating and those which go down through it and are reflected from its under surface. Incidentally they furnish an accurate measure of the thickness of the lacquer. The coat is in the form of a thin wedge, thickest at the bottom where the lacquer tends to settle by gravity before it dries. If there is only one blue-to-pink series (one fringe) it shows that the butt end (bottom) of the wedge is not more than 1/100,000 inch thicker than the top, and will therefore not on that account affect the light much, as the wavelength of light is about twice that amount.

Instead of Lastina, which is a collodion base lacquer, plain collodion or even New Skin dissolved in amyl acetate, one part to 12, may be used (John Pierce's method). Curtis also refers in an early paper to "a dilute solution of celluloid in amyl acetate," a possible substitute. A better looking, and in some cases a better, job of lacquering from an optical point of view, may be obtained as described by F. J. Hargreaves, F. R. A. S., well-known English amateur optician, in the "Journal of the British Astronomical Association" for May, 1928. He applies the lacquer "by spinning the mirror face upwards during drying, thereby distributing the lacquer symmetrically, though not necessarily uniformly in the radial direction. The mirror should be at the temperature of the room, which should be not lower than 60° F. The air of the room should be dry; moisture is fatal. The silvered surface

should be dusted lightly but thoroughly with the edge of a feather just before pouring on the lacquer. The lacquer should be poured on through a filter paper which has been cleared of dust immediately beforehand by pouring through it a liberal quantity of amyl acetate. It is not necessary to cover the whole surface to the edges; the liquid spreads evenly when the mirror is rotated, provided it is not started rapidly. Rotation of the mirror should be continued steadily until there is no doubt whatever that the coating is dry from edge to edge. This is most important. If the mirror is watched carefully at nearly grazing incidence, concentric interference bands will be seen after a minute or so, which rapidly contract toward the center and disappear. A very narrow marginal zone will, however, not be dry at this stage, and if the rotation is stopped at this time the liquid will flow inwards and cause a ridged, cloudy margin about one-eighth of an inch wide. The rotation should be continued for another two or three minutes, to insure that this does not occur. When completely dry the ridge at the margin is only about 0.25 mm. wide. It can be avoided by holding a swab of cotton-wool or soft blotting paper lightly against the edge during the whole process. The drying should not be hastened by blowing or heating in the early stages; hurried drying gives no time for the liquid layer to even itself out. When finished the coating should show a uniform interference color over its whole surface when viewed very obliquely; no colored bands should be visible." Mr. Hargreaves suggests using the turntable of a gramophone for this job. He found that about three revolutions per second was about right for a 6½-inch mirror. The excess lacquer flies off in a shower and the worker should not wear a dress suit when lacquering a mirror. It is expedient to practice on something besides the nicely silvered mirror before tackling the final job.

The turntable method is also used by Henson at the Mount Wilson optical shops.

If for some reason it is desired to remove the lacquer this may be done with amyl acetate and a tuft of absorbent cotton. Mr. Hargreaves states that the silver should then be given a light rub with chamois before relacquering, otherwise the lacquer will not flow readily and evenly over the entire surface. "The coating can easily be made too thin," he states, "particularly if the temperature is rather low. If this occurs (as shown by a perceptible dulling of the surface due to interference) it can be easily avoided at the next attempt, because after the mirror has been rotating for a short time the coating can be dried almost instantaneously by blowing on it. By choosing the right moment to blow, the thickness of the coating can be very easily controlled." Bell mentions removing an old damaged coating of lacquer in the same manner and burnishing the silver a bit, after which a fresh coat of lacquer was applied.

Young and Krotov of the University of Toronto found (see "Journal of the Royal Astronomical Society of Canada," November, 1929) that the reflecting power of silvered mirrors evidently is not so high as some of the standard tables of reflectivity state. For example, in the International Critical Tables the percentage of reflected light is stated to range from 94

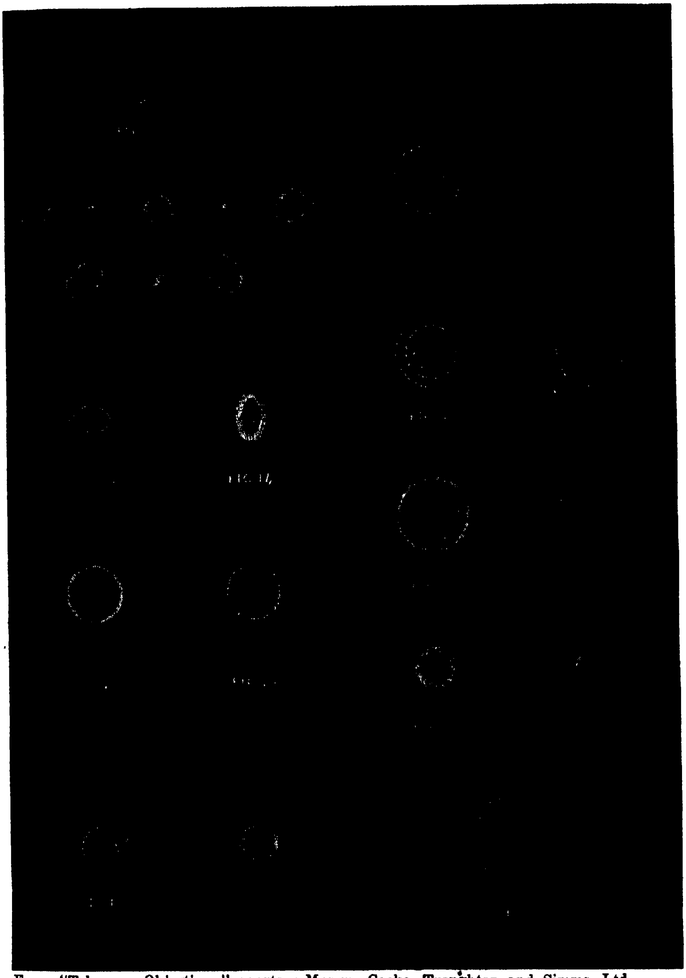
percent at 7000 angstrom units (red) to 90 percent at 4500 a.u. (blue) and 84 percent at 4000 a.u. (violet). These two workers found, however, that while new mirrors reflect in the red almost the amount stated, only about 76 percent of the light was reflected in the blue and 60 or 65 percent in the violet. After aging considerably, one of the same mirrors was still well up in the red, but had fallen to 63 percent in the blue and only 50 percent in the violet. "When the silver coat begins to look a little yellow," the experimenters state, "the reflecting power at wavelength 4000 to 3900 (violet) was not more than 50 percent."

We have at last made a mirror. All the refined, exacting work we did on glass, by means of abrasives, did not make one, though we called it a mirror. The mirror is a disk of solid silver which is so very thin in comparison with its diameter that it requires a rigid mechanical support. All that the glass does is to provide that support (and be the right shape!).

The Diffraction Ring Test is made on a star, by observation of the extra-focal rings. This has nothing to do with the knife-edge test, though that test too may be performed on a star by removing the eyepiece and placing a knife-edge across the end of the adapter tube, when the appearances will be the same as those of a mirror tested at the focus (Part I, Ch. I).

If the telescope, with an eyepiece giving it a magnification of 30 or 40 diameters for each inch of aperture, is focussed on some moderately bright star, preferably of 2nd, 3rd or 4th magnitude, and if the eyepiece is then pulled out or pushed in an eighth or a quarter of an inch, the image of the star will be seen expanded into an area of light. If the atmosphere is fairly steady, and especially if the observer persists for a few minutes in order to train his eye to a new and unfamiliar appearance, this area of light may resolve or tend to resolve itself into several concentric rings, perhaps perfectly round, perhaps distorted and, unless the air is steady, constantly shifting and changing and clearly visible only by occasional short glimpses. If the mirror is perfect and in perfect adjustment, and if the air is very steady, these rings can be made to look exactly like Figure 23 in the accompanying plate; except that, in the case of a reflector, the shadow of the diagonal will cover up the central rings, leaving in their place merely a black area. Note that in Figure 23 each ring is a little wider than the last, except that the outside ring is very considerably wider than its immediate neighbor; also that the dark interval between the rings likewise is progressively wider from center to edge.

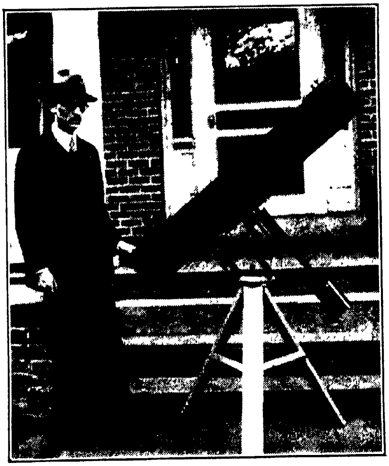
But, lest the worker suffer undue sorrow concerning his mirror, it can be said that such good fortune as to behold a perfect set of rings is relatively rare, and that "perfect" mirrors showing none of the bad symptoms indicated elsewhere on the same plate, at least in some degree, are made chiefly in Heaven. This plate is reproduced from the book "The Adjustment and Testing of Telescope Objectives," published by Cooke, Troughton and Simms, Ltd., of York, England, well-known manufacturers of engineering and



From "Telescope Objectives," courtesy Messrs. Cooke, Troughton and Simms, Ltd.

scientific instruments. The various appearances indicated on it are treated in greater detail in that book than they can be treated in the following briefer comments.

For good telescopic seeing a night when the stars are sharp and "twinkly" is likely to be much inferior to a night when they stand out less distinctly; in fact some of the best seeing is available on nights when the air is slightly



A square box tube for a six-inch mirror. Telescope made by Hugh G. Boutell of the Bureau of Standards.

hazy. The same will usually be true of conditions, and for the same reasons, when testing the mirror by means of its extra-focal rings. However, if the rings show ideally for even an occasional tenth of a second on a night when the atmosphere is unsteady, this and not the sadly distorted rings seen during the rest of the time, may be taken as a gage of the mirror's probable worth; and if one persists long enough a "perfect" night may come.

Figure 10 includes three appearances. In *a*, which is lopsided with the smaller end the brighter, the mirror (or objective lens, for the same characterizations apply to both) is not square with the telescope. Move one side of the mirror or the other by means of its adjusting screw, and note whether the rings become less lopsided or more so; if the latter, move it thereafter in the opposite direction while adjusting, and continue until the rings are round.

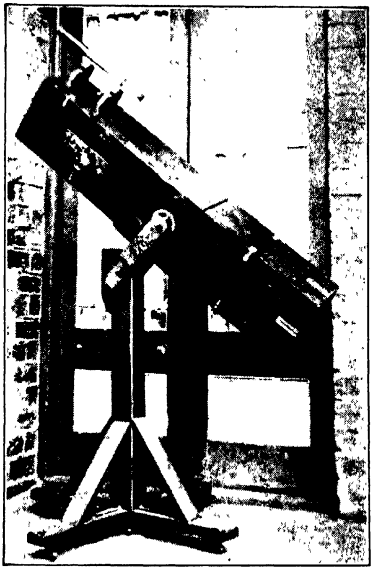
In *b*, somewhat below, and *c*, top row, the eyepiece has been placed as close to the focus as possible ("best focus"). In *b* the rings show on one side of the star image and are fanned or tailed out; in *c* they are farther

fanned out into a distorted pattern. This too shows that the mirror is not properly squared-on.

In Figure 11 the previous fault has been partly remedied, a high-powered eyepiece has been put on and moved up closer to the focus. This reveals fewer rings. More delicate movement of the mirror screws will be required at this later stage of adjustment.

Figure 12 includes eight different appearances: top row, left to right, *a, a', b, b', c;* bottom row, *d, d'', d'.*

a is related to Figure 23, indicating a perfect mirror, but again the observer should remember that the central rings will be covered by the black shadow of the diagonal or prism; also that each support for the diagonal



A seven inch telescope with square box tube of wood—simple to make, relatively free from temperature troubles and as neat as any. Made by P. J. Naudé of Johannesburg, South Africa.

may reveal itself by a delicate streak traversing the appearance from center to edge (diffraction).

a' is the star image *at the focus,* showing one "spurious ring." This spurious or outer disk is normal, not in the sense that something is necessarily wrong when it cannot be seen, but in the sense that theoretically it should

always be seen. If one or more spurious rings are not seen the fault may be the state of the air and not the telescope. Compare this sketch with Figure 17, which also shows the star disk or image of a star exhibited by a perfect objective or mirror but with higher power. Both of these are *at the focus;* they are not extra-focal images.

b is extra-focal and suggests the triangular, while *b'* to its right is the same mirror at the focus, the central image being similarly distorted and the spurious disk broken into three equilateral segments, not all of which show clearly in the reproduction. These suggest flexure. Doubtless a flotation system for the mirror would change these segments into a full circle.

c is simply one more of the 1001 or 1,000,001 possible forms which the images may show on different telescopes due to various peculiarities. It suggests flexure.

The three appearances in the lower row denote astigmatism. If a mirror has a certain radius of curvature across one diameter, and another radius of curvature across a different diameter, the reflected rays obviously will not come to a focus at equal distances from it. *d* shows the effect on an otherwise good image of a mirror which has a longer focus in a "northeast-southwest" direction (speaking mapwise) than at right angles to that direction. If we now pull the eyepiece out farther we shall then be past the focus of the first rays and, since they meet and cross over, the ovals will be turned through 90° as in *d'*, the last of these eight figures; between these extremes the oval will be turned at intermediate angles. *d"*, between these two, is the appearance caused by astigmatism on the central image and one spurious disk at the best focus.

Before condemning the mirror see whether the astigmatism, if any, is in your own eye or in the eyepiece. Twist the head through an angle of 90°, more or less; if it is the eye which is astigmatised the axis of the oval will follow around with the head. Rotate the eyepiece; if the astigmatism is in this, the oval will rotate. (One interesting combination is when the oval is long at one eye position but round or more nearly round at right angles to it. Here both the mirror and the eye are astigmatic.) It may require a higher power to detect a smaller degree of astigmatism in the mirror, but a low power reveals the same fault, if in the eye, and to better advantage.

If there is astigmatism in the eye, spectacles will correct it but these are often a nuisance when using a telescope, for they may prevent the eye from coming up closely enough to the eyepiece to take in the whole emergent pupil. It may in some cases be worth while to add a correcting lens to the eyepiece and remove the spectacles. A small cap may be designed and fitted over the eye end, and one of the observer's individual spectacle lenses trimmed down and placed in it. Since the position of the tube of the telescope will vary, this auxiliary device should be arranged so that it will rotate, and preferably a single detachable lens cap should be made to fit all of the observer's eyepieces.

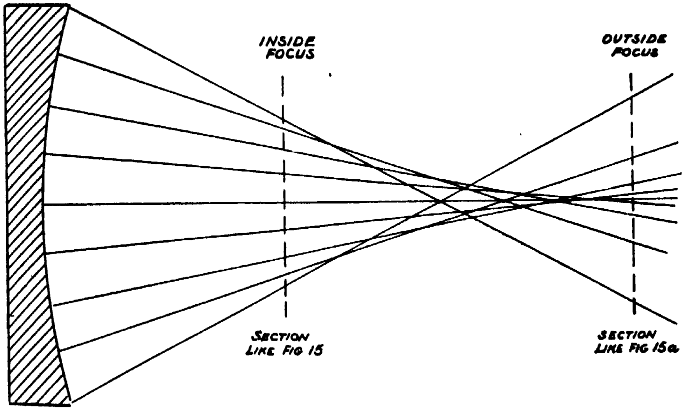
Figures 13 and 14 are sections respectively a very little way inside focus and a very little way outside focus, under high power, showing astigmatism.

Figure 15 exhibits undue progressive strengthening or brightening, or

both, of the outer rings, and weakening of the inner rings. If seen inside focus it denotes under-correction; if outside focus, over-correction. Figure 15*a* is the reverse of the last. If seen inside focus this denotes over-correction; if outside focus, under-correction.

The distances from focus chosen for this test are such that about the number of rings shown, and no more, will be seen. The outer ring is similar in appearance to that of Figure 23, but the adjacent rings are proportionately more strongly stressed; the curve of change is steeper.

If no under-correction or over-correction is found at some distance from focus the eyepiece should be shifted closer. Here there will be fewer rings,



Drawing by Russell W. Porter, after the author

as in Figures 16 and 16*a*, which are analogous to Figures 15 and 15*a*. The reason for shifting closer to the focus may be understood if rays from each zone of an under-corrected and an over-corrected mirror are sketched on paper. If there is much under-correction or much over-correction the two sets of rings will cross at a considerable distance apart along the axis; if little, they will cross nearer together. Some of the rings will be unduly enhanced because rays which cross one another pass on to combine with rays from other zones; others will be weakened because rays which have thus jumped the track are absent from their rightful place.[1] When this is clearly

[1] See sketch. As constructed, rays start from zones on the under-corrected (ellipsoidal) mirror at equal intervals across diameter and cross the axis at intervals which increase toward the mirror. The cross-section marked "inside focus" clearly reveals greater crowding at the outer edge, corresponding to Figure 15 from the Cooke, Troughton and Simms book. The other cross-section, markcd "outside focus," reveals the opposite, corresponding to Figure 15*a*. For an over-corrected mirror (hyperboloid) the rays should be started from the same places on the mirror but the intervals along the axis should decrease toward the mirror.—*Ed.*

understood, the reason for testing with different numbers of rings will be obvious: it is not any given number of rings, in itself, that is desired, but the number used is a measure of the point along the axis. at which the various rays will be intersected by the eyepiece.

Under-correction refers to a mirror which is ellipsoidal (prolate spheroid); the marginal rays come to a focus nearer the mirror than the central rays. Over-correction refers to a mirror which is hyperboloidal; the marginal rays come to a focus farther away from the mirror than the central rays. In both cases parallel incident rays are assumed.

The extra-focal tests reveal the condition of a mirror at the time they are made, and allowance should be made for changes in figure due to changing temperature. But, which way should allowance be made? This, in a sense, begs the question, which is: what really *are* the effects of changing temperature? Not all are agreed concerning them.

Figure 17, at the focus, is "the spurious disk or image of a star yielded by a perfect objective and viewed under a very high magnifying power." The ring will be visible only on rare nights. Very rarely two rings may be visible —perhaps even three. The larger the relative aperture the smaller the disk and its system of rings.

Figure 18, like Figure 12*b*, has a triangular suggestion and in the Cooke, Troughton and Simms book from which the plate is reproduced this is ascribed to an objective lens flexured by being mounted on three supports. (Figures 17 and 18 are rather faint in the reproduction.) Doubtless the analogous effect from a mirror too large for so few supports (see Part X, Ch. II) would not be altogether dissimilar; at least it will usually show some "threed" appearance.

Figure 19 with 19*a* is another pair; so are Figures 20 and 20*a*, and Figures 21 and 21*a*—all denoting raised or depressed zones. Zones cause the rays to focus at different distances along the axis and to pass on and across one another, meeting other rays from other parts of the mirror, and not only to aggrandize these places but rob their own. For detecting zones the eyepiece should be placed a long way from focus, revealing about a dozen rings, and for their proper illumination more light is needed—a brighter star may be chosen.

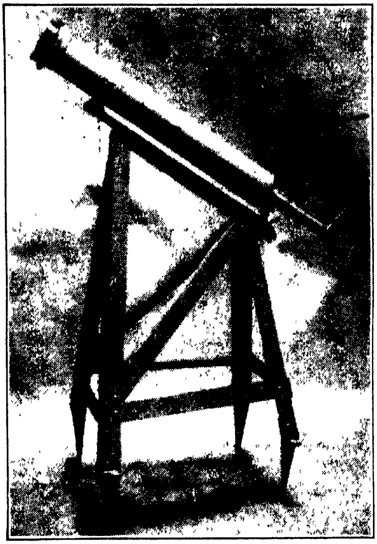
Figure 19, inside focus, and Figure 19*a*, outside focus, represent a bad case of zones, more easily interpreted for position (as the zones all are, for that matter) by means of the knife-edge test than by the present one.

Figure 20, inside focus, or Figure 20*a*, outside focus, denotes an intermediate zone of shorter radius than the ideal curve of the rest of the mirror, and rather nearer the edge than the center.

Figure 21, inside focus, or Figure 21*a*, outside focus, denotes a raised center. The drawings are for a refractor but the diagonal on a reflector will rob the members of this pair of most of their contrasts and render these effects difficult to detect.

Figures 22 and 22*a* represent a perfect mirror, respectively outside and an equal distance, but not far, inside focus, under high power. Both appearances should be exactly alike.

Figure 23 is the appearance of a perfect mirror when the eyepiece is far enough from focus to take in eight rings. Note the perfect roundness of all rings, the perfect progression in width of rings and of dark intervals, except that the outer ring is legitimately broader and brighter than the same progression calls for. The same appearance should be had outside focus as inside, and at equal distance. It speaks loudly in praise of a mirror if it



One of the six 4-inch refractors designed by Porter, for use in connection with the selection of the site for the 200 inch telescope. Selection of a site is made largely on a basis of atmospheric conditions and, since any star will serve to gage these, Polaris was chosen because a convenient fixed telescope could then be used. The eyepiece is a compound microscope, the telescope magnifying 700 diameters, and the steadiness of the air is rated at different night hours by the amplitude of the lateral shifts of the star image with regard to the cross-hairs, the shifts being caused by atmospheric conditions.

can pass this test. However, as Captain Ainslie has pointed out, most eyepieces have spherical aberration of their own, low-powered ones the most, hence if the mirror seems perfect with a high-powered eyepiece but undercorrected with a low-powered eyepiece this may be due to the eyepiece. On a rare night the appearance of a perfect mirror should be as good or better than this figure, which is not idealized. But, rare is a perfect mirror, and rare is a perfect night!

As in the case of the knife-edge test, the observer's judgment and dis-

cernment will become very much more critical after a few weeks of practice in observing the various appearances just described.

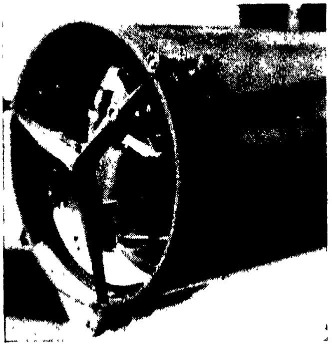
Elementary discussion of the optics of diffraction will be found in any college physics text-book, though not, of course, as applied specifically to the telescope. The latter application is explained in "Telescope Objectives," the book from which most of the data just presented were abstracted. Briefly, these rings are due, as Captain Ainslie states in "The Splendour of the Heavens," to "the mutual interference between light waves from the various parts of the aperture on their way to the focus."

Why cannot diffraction rings similar to those just dealt with be seen by means of an artificial star—that is, a pinhole? They can. There is no essential difference in theory between the two sets of conditions. However, some special refinements must be introduced. J. R. Haviland of New York has experimented with this interesting problem. First, an actual star subtends an extremely small angle, so the artificial star used must be very small. Haviland makes such pinholes by stacking a number of small sheets of tinfoil (in practice, one long strip folded zigzag) on a hard surface and pressing a fine needle through a number of them. The last hole thus made will be the smallest and may happen to be very small. The others are discarded. This tiny pinhole demands extremely powerful illumination if the rings are to be seen at focus, but ordinary filament illumination will reveal the extra-focal rings. Finally, it must be remembered that the real stars used in extra-focal tests are at "infinite" distance and that they therefore send parallel rays; while artificial stars are usually placed at the average focus of the mirror and send convergent rays to it. Therefore, in order to obtain normal rings, the mirror must either be a sphere or, if a paraboloid, the artificial star must be at something comparable to "infinite" distance. Here Haviland employs the bright spot on a Christmas tree ball placed in the sunlight at several hundred feet distance. The rings actually will show at the average focus of a paraboloidal mirror but will not have a normal appearance.

Adjusting Telescope by Equatorial Star: If Polaris is hidden the telescope may be adjusted by means of an equatorial star—in fact this method is as easy as the other, and does not require sitting up half of the night to see Polaris in different positions. Choose some convenient star in the south, close to the meridian and reasonably near the equator, though one higher up will serve only relatively less well. Look up its declination, aim the telescope at it, and tentatively adjust the mounting to that declination. If it should happen the first time that the polar axis is in a vertical north-and-south plane, that is, in the plane of the meridian, this would complete the declination adjustment, but the chances are that it is tilted a little to east or to west. If so, when the star moves in R.A. the telescope, also moving in R.A., will follow a diagonal line either above it or below it, departing farther and farther from it. So leave the telescope for a half hour or an hour and, on returning, swing it in R.A. until it is either under or over the same star. If the star has climbed, relative to the telescope, the polar axis must be tilted either one way or the other, depending on the type of telescope

(number of inversions in the optical train) and perhaps most quickly and assuredly arrived at by trial and error.

Once more set the telescope on the star (or on any other convenient star) and go through the same performance. On this second approximation it possibly will be found that the star stays in the field but crawls up or down toward the edge of it after a time. Assuming that the field with a one-inch eyepiece is about one-half degree in diameter, make the corresponding finer adjustments by judgment.



Left: Support for a 10-inch mirror made by A. W. Everest of Pittsfield, Mass. A three-legged spider carries three triple-point supports, each of which is a T, with the point of balance placed two thirds of the way from bottom to top of the T. The principle of weight distribution differs slightly from that given by Hindle, but the difference is slight on a small mirror. Right: Support for a 9-inch mirror made by Cyril N. Wates of Edmonton, Alberta, Canada. Note three adjustment screws, three metal triangles and the Hindle-type lugs, which keep them from turning. Even on mirrors (good ones) of 9- or 10-inch size flotation systems seem to improve definition. It will be obvious that no flotation system, however elaborate, can improve the performance of a badly figured mirror. Compare the two illustrations above with the Hindle data on page 233. In a letter, Everest says, "I have divided the mirror into nine sections of equal weight, and then placed a support at the center of gravity of each section. For a flat, this would bring the points farther in than Hindle's radius of equilibrium method. But for a concave, where the central sections must have more area than the outer ones, to have the same weight, the points move out and about coincide with Hindle's—to the first two significant figures on an F/8 of thickness to diameter ratio 1.6."

If two approximations do not give complete adjustment make three.

The polar axis now lies in the plane of the meridian but the chances are that there is a small outstanding error in the declination. It is a simple matter to raise the south or the north side of the telescope as a whole, until the declination on the circle corresponds to that of a star.

The adjustment for R.A. is relatively easy: simply rotate the mounting horizontally until the star is in the center of the field at the instant it ought to be there (for this, see Part I, Ch. VI; also Miscellany note on "Setting

Circles"). This, too, may be accomplished by means of first, second and possibly third approximations.

Conduction and Radiation of Heat in Glass and Metals: Heat is transported by three methods, radiation, conduction and convection, as explained in textbooks of physics. In the case of solid materials used for optical parts convection may be left out of the discussion, hence only two of these three methods remain, namely, radiation and conduction. Glass transmits waves of radiant heat between approximately .0003 and .0007 millimeters in length (which are the ones we sense as visible light) and longer waves up to about .003 millimeters in length. For still longer waves it is as opaque as a brick wall, yet these longer waves make up the bulk of the radiant heat with which a piece of glass in a telescope is called to deal. The metals, of course, are opaque to all of these wavelengths of radiation.

When it comes to conduction, however, the cases differ: The metals conduct heat from 100 (for iron) to 1000 (for silver) times as readily as glass. The latter, not being capable of transmitting much radiant heat, must get rid of it by conduction and in glass this is a very slow process. Glass is used for telescope disks, not because of it bad heat-conducting and bad heat-transmitting qualities, but in spite of them. It has other advantages.

More about Finders: The simplest finder—some say the best of all—is a pair of home-made gunsights, one member being a ring and the other a point. Before putting anything into finished form a few outdoor tests on visibility at night, using wires variously bent, may save surprise and disappointment later on. Luminescent paint may prove useful on the sights.

Two simple lenses costing about a dollar can be made into a finder of a kind. Let the front lens be an inch or so in diameter, with a focal length of 8 or 10 inches, the eye lens an inch or more in focal length and whatever diameter is readily available—say, half an inch. Many kinds of cheap pick-me-up magnifying glasses will be found to contain suitable lenses for this purpose. Lenses may be purchased from Bausch and Lomb, or even home-made, following instructions in John M. Pierce's "Hobbygraph" No. 1, on "Amateur Lens Making." Such a finder will scarcely be achromatic, but it will find—and at low cost. Separate the two lenses by a distance equal to the combined focal lengths of the two lenses. The focal lengths may be ascertained by measuring the distance from each lens to the smallest, sharpest image of the sun it will give. Place the curved side of the eye lens next the eye if it is a plano-convex, as it will then show less spherical aberration. Two spectacle lenses may also be used. No tube is needed, the lenses being merely attached on supports of some kind on the main telescope.

Cross-hairs are discussed in an earlier note on *"Finders,"* elsewhere in the Miscellany. If used at all—and they are not really needed since almost anyone can center the finder on a given star closely enough to place the star in the field of the main telescope, provided it has a low-powered eyepiece—they should be placed in the focus of the eyepiece. For night use the cross-hairs, if any are provided, should not be spider-webs but No. 30 to No. 36 wire, which is large enough to be visible in the dark. Instead of cross-hairs a

small ball on the end of a wire may be placed in the focus and bent about until it is in line.

John M. Pierce's "Hobbygraph" No. 3 tells how to design and make a very good finder having a one-inch objective lens. The objective lens is achromatic but the eyepiece is a simple lens. Such a combination will give far less color effect than the reverse—that is, than a simple objective lens and a compound eyepiece, but as a finder rather requires a broad field, it will be improved if provided with a two-lens eyepiece.

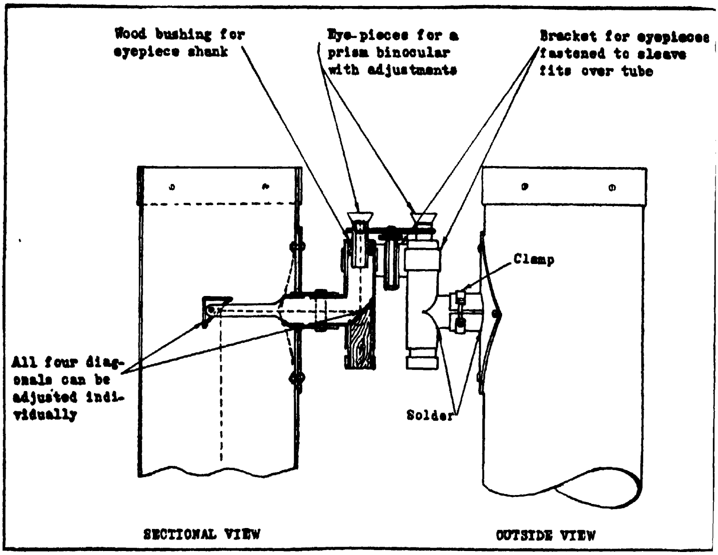
A finder should give a field at least three to five degrees in angular diameter—15½ to 26 feet wide—at 100 yards. For example, Carl Zeiss, Inc., lists three typical finders: The first has a 1-inch objective lens of about 8 inches focal length and a 1-inch eyepiece. It magnifies 8 diameters and has a field 5° 13′ in angular diameter. The second has a 1³⁄₁₆-inch objective of about 12 inches focus, 1³⁄₁₆-inch eyepiece, magnifies 10 diameters and gives a field 4° 10′ in diameter. The third has a 1¾-inch objective of 14 inches focus, a 1-inch eyepiece, magnifies 15 diameters and has a field 2° 47′ in diameter. A finder designed about like the first of these three would probably be the best for general use. Comparing such a telescope, made as a finder, with binocular specifications—for example, those in a Bausch and Lomb catalog—we have for the latter: 1-inch objective, 8 diameters, field 6° 30′ in angular diameter or 34 feet at 100 yards. Thus the binocular and the regular finder are not very different. A prism binocular is simply two telescopes, jack-knifed by means of prisms in order to gain compactness. Half of a binocular or even a whole one makes a splendid finder.

Light Gathering Power; Binoculars: If we divide the aperture of a telescope in millimeters by the diameter of the Ramsden disk, emergent pupil or exit pupil (variously called) we derive the number of diameters it magnifies. Conversely, if we divide the aperture in millimeters by the number of diameters it magnifies, we derive the diameter of the exit pupil. Among opticians it is a convention that the square of the diameter of the exit pupil, expressed in millimeters, is the "light gathering power"—sometimes termed light transmitting power, or merely light power. This term is chiefly confined to the binocular trade and "*l.g.p.*" runs up, in the case of binoculars costing about 100 dollars, to about 50 and occasionally to 60. It is usually stamped on the binocular; *e.g.*, 7 × 49, meaning 7 diameters, *l.g.p.* 49. On smaller, more common sizes, it is about 25 or 30.

A binocular having a *l.g.p.* of 49 and magnifying 7 diameters—the expensive type mentioned—has an exit pupil 7 millimeters, or a shade over a quarter inch, in diameter, since 49 divided by 7 equals 7. Now, the opening of the human pupil in daylight is only about 3.8 millimeters, roughly ³⁄₁₆ inch, in diameter. How then can all the rays get in? They can't.

In daylight the outer 1.6 millimeters, some two-thirds more or less, of the large 7 mm. exit pupil does not count. This part is for use on dull days, or at dusk, or after dark, when the pupil of the eye will open more widely. At night, with such binoculars, our eyes will take in the whole 7-millimeter exit pupil, hence these are the closest existing thing to the mysterious "night

glasses" we hear about in wild exaggeration, mainly in stories where facts don't matter. The argument for large binoculars is similar to that in favor of a camera with a large lens, say an $f/3.5$, most of which you do not use on ordinary occasions but which it is nice to have handy in case of occasions which demand extra facilities. It is "reserve power."



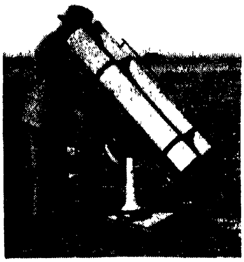
Drawing by Hilmer Hanson

A six-inch binocular made by Hilmer Hanson of Holdredge, Neb. Both mirrors were ground and polished alternately on the same tool—several times per wet when it came to the fine grinding and polishing. The two mirrors were tested individually, also simultaneously with binocular eyepieces.

In the case of a telescope of more conventional specifications—for a binocular is really a telescope or rather a pair of them—the *l.g.p.* will have a relatively low number, and there will be little need to worry about the exit pupil being too wide for the eye. For example, take a 6-inch mirror of 48 inches focal length, used with a one-inch eyepiece. In round numbers, this works out as follows: 150 mm./50 = 3 mm., the diameter of the exit pupil. That diameter squared, or $3 \times 3, = 9$, the *l.g.p.* of the telescope.

Suppose we had a mirror of short focus, a 6-inch of $f/5$, or 30 inches focal length, with an eyepiece of long *e.f.l.*—say one-inch. Then 150 mm./30 = 5 mm. This exit pupil is somewhat above the diameter which the eye can

receive in daylight but this does not matter, since there is plenty of illumination in daylight for terrestrial uses; while at night the 5-millimeter exit pupil will slide nicely into the eye, and with room to spare. Only in rare

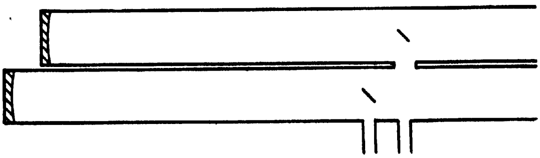


Mr. Hanson and his reflecting binocular.

cases will the outside diameter of exit pupil be a factor to watch in designing a telescope.

According to Dall the resolving power of the eye reaches its limit with a pupil of 3 or 4 mm., as at this point the retinal rods and cones have dimensions at least as large as the separating powers of the aperture, even with perfect sight.

Notes on the Eyepiece: Nominally, in a Huyghenian eyepiece the focal length of the field lens is three times that of the eye lens. In practice this varies somewhat from the prototype, for there are many modifications. In



Drawing by F. D. McHugh, after Capt. M. A. Ainslie

The arrangement for a binocular used by the elder Herschel. Provision should be made for adjusting to different observers' inter-ocular distances.

general, the ratio will vary with the power. With low powers it may be 1:1.5 or 1:2. The 1:3 ratio pertains more to the higher powers. As stated by Bell ("The Telescope"), the exact figure will also vary with the amount of overcorrection in the objective (or mirror) and undercorrection in the observer's eye. The separation may be adjusted by trial on the telescope, at the point where the best color correction is found.

Bell's entire chapter on eyepieces should be read by anyone who aspires to make more than one or two very simple eyepieces and, of course, the late Professor Hastings' contributions, Part VI of the present volume, should not be missed. The article on "Eyepieces," in Volume 5 of Glazebrook's "Dictionary of Applied Physics" contains 5 pages of eyepiece theory (mathematical). John M. Pierce's "Hobbygraphs," No. 2 on "Eyepiece Making" and No. 1 on "Amateur Lens Making," contain much practical help, the former giving working formulas for the design of Huyghens and Ramsden eyepieces of different *e.f.l.* Orford's "Lens Work for Amateurs" contains some practical shop suggestions.

The following is from Ellison's "The Amateur's Telescope": "The Huyghenian eyepiece consists of two plano-convex lenses, having their plane sides both toward the eye. The focal lengths of these should theoretically be as 1:3, the eye-lens being the shorter, and their distance apart should be half the sum of their focal lengths. These dimensions are, however, rarely adhered to in practice. The German form of Huyghenian has a meniscus field lens with the concave side toward the eye. The Ramsden eyepiece is simply a pair of equal plano-convexes, with their convex sides next each other and separated by a distance slightly less than the focal length of either. The Kellner construction, sometimes used for low powers, has a double convex field lens with radii as 2:3, the deeper curve being toward the object-glass, and a plano-convex eye-lens, placed as in the Huyghenian, and distant its own focal length from the field lens. Browning's achromatic eyepieces are Kellners, with an achromatic combination for eye-lens, the side next the eye being concave.

"To ascertain what are the powers of a set of eyepieces, a dynamometer is necessary. The most usual and cheapest form of this useful little instrument we owe to the Rev. E. L. Berthon. It consists of a pair of metal straightedges, fixed at a very acute angle to each other, one edge being provided with a scale of 1-100 inch divisions, showing the distance between the edges at each division. It can be used as a wire gage, or to measure the thickness of sheet metal, etc. As a telescopic dynamometer it is used by measuring the diameter of the 'Ramsden disk.' If the telescope be directed to the open sky, a sheet of white paper, a whitewashed wall, etc., the eye placed about 12 inches behind the eyepiece, sees in it the image of the object-glass as a sharp bright disk. This is the 'Ramsden disk.' Being a real image, and in front of the eye-lens, it can be focussed with a magnifying glass or pocket lens, and a very sharp view of it obtained. The dynamometer is now placed in position and adjusted till each edge is tangent to the disk of light. The scale is read at the point of contact. The aperture of the telescope, divided by the diameter of the Ramsden disk, gives the power of the eyepiece on that particular telescope or any other of the same focal length. A telescope is not even necessary for the measurement. The image of a window-pane, clock-dial, or any other sharply-defined object can be used, and the result will be the power of the eyepiece on a telescope whose focal length is the distance of the eyepiece from the object used. Then, taking this power as a divisor and the focal length as a dividend, the quotient

is the equivalent focus of the eyepiece. For example, on a 5-inch telescope the Ramsden disk was 1/10th inch diameter. Power was therefore 5 inches ÷ 1/10th = 50. The focal length of the o.g. was 75 inches : 75 ÷ 50 = 1.5. Equivalent focus of eyepiece was 1½ inches. Again, with another eyepiece on same telescope, the Ramsden disk measured 0.03 inch. Power was therefore 5 ÷ 0.03 = 166. Equivalent focus of eyepiece was 75 ÷ 166 = 0.45 inch.

"It is necessary, before making these measures, to make sure that the aperture of the o.g. is 'clear'—*i.e.*, that none of the stops in the tube are narrow enough to stop any portion of the cone of light converging from it. Any other instrument capable of giving an accurate measurement of the diameter of the Ramsden disk can be used as a dynamometer, an ordinary micrometer calipers being an excellent substitute, especially if its two contact faces are lightly smoked in a candle flame to prevent reflection from them. It is sometimes stated that the equivalent focus of a Huyghenian eyepiece equals half the focal length of its field-lens. If this were true it would be easy to measure powers, as the field-lens, being the larger of the two, has a fairly long focus and easily measured directly. But, unfortunately, it is only true if the proper proportions for a Huyghenian (foci as 1 : 3 and distance apart = 2) are strictly adhered to by the makers, which they rarely, if ever, are.

"It may be well to state, in conclusion, that the equivalent focus of any two-lens eyepiece can be obtained from the formula:

$$\frac{f_1 \times f_2}{f_1 + f_2 - d}$$

where f_1 and f_2 are the focal lengths of the components, and d their distance apart. The distance apart of plano-convex lenses should be measured from their *convex* faces, not from the plane ones, as might *prima facie* be supposed. The only drawback to this formula as a means of measuring powers is the difficulty of obtaining an accurate measure of the focus of very small lenses, such as the eye-lenses of high powers always are."

The following statements were chosen from an article by M. A. Ainslie, in the *Journal of the British Astronomical Association*, Nov. 1930: "The amount of the spherical aberration of a given eyepiece varies very nearly as the square of the aperture ratio of the object glass or mirror with which it is used. The same eyepiece used with a mirror of ratio $f/5$ will have 9 times as much aberration as with an object glass of $f/15$, and it may be very serious. In short, the Huyghenian does very well for a refractor for all powers, but it is not good enough for a reflector. If used for a speculum of aperture ratio $f/5$ a 1-inch Huyghenian eyepiece would require the speculum to be *over*-corrected to the extent of about one-twelfth of an inch."

In a private communication, H. E. Dall of England, an engineering instrument designer who has made a number of interesting telescopes of amateur size, and who makes Tolles eyepieces (Part IV, Ch. II, C.), points out the interesting fact that "when using a standard form of Huyghenian giving a power of, say, 20 per inch (a fair average) the spherical aberration of the

eyepiece gives as much error in the image as the difference between a sphere and a paraboloid for about 6-inch aperture, this being independent of angular aperture. Under these conditions," he states, "it is rather futile to figure to a precise paraboloid. The remedy is of course to use eyepieces of small aberrations."

To make the solid metal type of lap which has been in use ever since the year 1 for grinding and polishing small spherical lenses such as those used in eyepieces has always required much labor and patience, and to keep it spherical has required further labor and patience. Within relatively recent years large balls for bearings have become readily and widely available. In 1926 John M. Pierce made lead laps by hammering such balls into chunks of lead. George Croston of Tacoma has improved this method, in a similar way making accurate laps of sheet metal. His method is essentially as follows: "Lay a sheet of copper, lead, soft steel or other soft metal on a ring; place a steel ball on this and, with a vise or hammer, force the ball into the sheet metal. The latter may be about $\frac{1}{16}$ inch thick, and the ring should have a hole slightly smaller than the full diameter of the ball. For extreme accuracy press both ball and sheet metal into a block of lead. As the lap wears out of shape during use it may be restored in the same way it was formed.

"The cup-shaped lap thus formed is pitched to a rotating spindle, similar to the lens in Part I, Ch. XI, Figure 58, at *a*. Use a different lap for each grade of abrasive. In grinding with the last two grades of abrasive hold the lap in the palm and rotate the lens with the other hand, using pressure. If the motor drive is used on these final sizes the excessive speed will deprive the center of abrasive by centrifugal action and the edges of the lens will be ground too much. On the final stage a lead lap will give a finish which will polish in 10 minutes with rouge.

"To make the pitch polishing lap turn the spindle vertically, pour melted pitch into the concavity of a spare lap (a spindle of wood with a concavity concentric with the lap turned in one end may be substituted for the tubular spindle, either here or at the outset) and, while the pitch is still melted, lay on it a patch of silk or cotton. Before the pitch entirely sets, dip the lens in cold water and start the spindle rotating. Press the lens into the cavity, making it run true."

Alan R. Kirkham of Tacoma furnishes the following note: "Serious defects in small lenses for eyepieces may be revealed by holding the lens at such a distance from the eye that a distant street lamp appears completely to illuminate the lens, and then introducing a Ronchi test grating very near to the eye. The figure of the lens will be indicated, just as in Part X, Ch. VIII, by the bands then observed."

Cassegrainian notes: A diagonal may be used to reflect the cone of rays to one side of the tube, instead of allowing them to pass through a perforation in the primary. This kind of construction is used on the 100-inch telescope and others of importance. As pointed out by Horace D. Dall (*Journal of the British Astronomical Association,* March 1931), it permits the eye-

piece to be located near the declination axis where the observer will find it more comfortably accessible. It also removes the body heat of the observer farther from the mirror. However, it reverses the image. A pentagonal prism will keep the otherwise reversed image straight but would be expensive.

Ritchey, in his work "On the Modern Reflecting Telescope and the Making and Testing of Optical Mirrors" treats the Cassegrainian as the special type mentioned above. Since there have been frequent requests to know just what Ritchey did say in this rare work, the *whole* of his comment on the Cassegrainian is quoted from it herewith. As will be seen, the comment is rather limited:

"The writer has recently made two convex mirrors of different curvature, for use with the 2-foot reflector. These give equivalent focal lengths of 27 and 38 feet respectively.

"Fig. 14 shows the arrangement of mirrors employed in the 2-foot reflector when used as a Cassegrain; a small diagonal plane mirror is used at *m*, to avoid the necessity of a hole through the center of the large concave

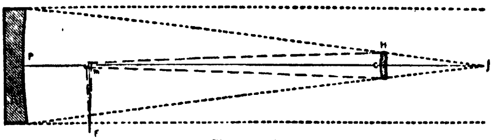


FIG. 14.

mirror. *P* is the paraboloidal mirror, with its focus at *f*; *H* is the hyperboloidal mirror, the secondary focus or magnified image produced by the combination being at *F*; the point *c* is the center of the hyperboloidal surface. Calling the distance $fc = p$ and the distance $cm + mF = p'$, then $\frac{p'}{p}$ represents the amount of amplification introduced by the convex mirror. The radius of curvature *R* of the spherical surface to which the convex mirror is ground and polished preparatory to hyperbolizing is found with sufficient accuracy for all practical purposes by the formula

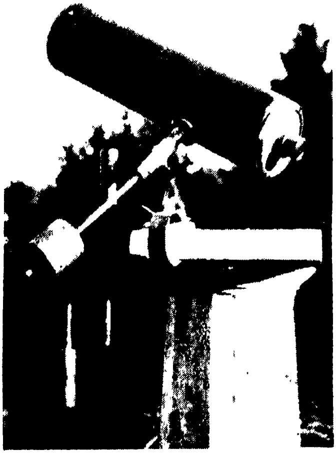
$$\frac{1}{p} - \frac{1}{p'} = \frac{2}{R} \text{ whence R} = \frac{2\,pp'}{p'-p}$$

"For example, let the focal length of the paraboloidal mirror *P*, Fig. 14, be ten feet; let $fc = p = 2$ feet and $cm + mF = p' = 8$ feet. Here $\frac{p'}{p} = 4$; the image of the moon or other celestial object produced at *F* is therefore four times larger in diameter than it would be at *F*, the focus of the paraboloid; and $R = \frac{2\,pp'}{p'-p} = 64$ inches."

In Part X, Hindle recommends an eye stop for the Cassegrainian, to delimit the Ramsden disk, and this is the most common method of cutting

out the direct light of the sky. An alternative dodge is a short conical tube with its small end fixed permanently through the perforation of the primary and into the cell. This delimits the light entering the eyepiece to the secondary cone. This tube extends forward from the mirror.

A point not often mentioned in favor of the Cassegrainian is the fact that the long *e.f.l.* and slender cone of light favors the eyepiece. This is explained by Captain Ainslie, in the note on "*Eyepieces.*" The effect, in a



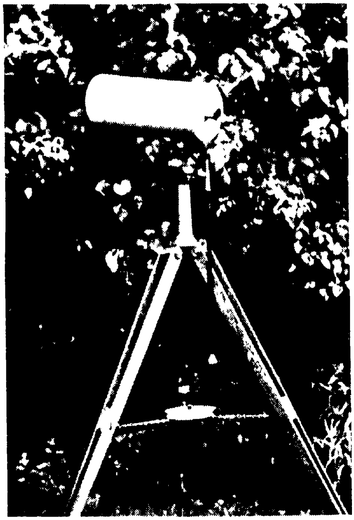
A 4-inch Cassegrainian built a number of years ago by John M. Pierce. Primary f/5; overall f/20.

Cassegrainian of $f/20$, would be the same as in the case of a refractor, or in a Newtonian reflector, of the same focal ratio.

The Cassegrainian is essentially for the observation of fine lunar and planetary detail; it has a small field and for general observation, rather than particular observation, it will be likely to prove disappointing. There is no difference in this respect, between a Cassegrainian of $f/20$ and a Newtonian of $f/20$.

Alan R. Kirkham contributes the following note. "When adjusting the optical train of a compound telescope, the first approximation may be made as follows: Direct the telescope toward a bright planet or a distant street lamp and replace the eyepiece with a grating of the kind used in the Ronchi test, placing it a trifle inside focus. The characteristic bands will be seen,

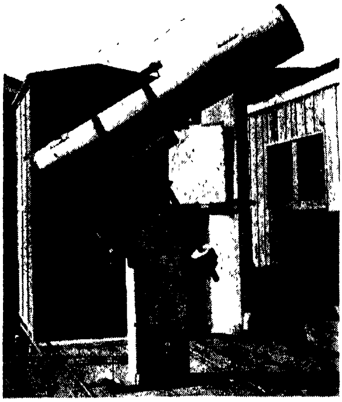
appearing as if they were on the secondary mirror. These bands will show astigmatic shapes with the slightest misalignment of prism, secondary, primary or adapter tube, spreading more at one side than at the other—that is, diverging. If the bands do not appear almost straight (temperature changes sometimes bend them one way or the other), there is a serious error in the figuring of the mirrors, primary or secondary or both. As will quickly become apparent when performing this test, stiffness in the various parts of the mounting is essential."



This compact modified Cassegrainian, made by Horace E. Dall of Luton, Bedfordshire, England, is said to be the smallest and lightest telescope of its aperture (6 inches) and power in the world. Length 19 inches. Aluminum tube. Weight complete with finder, only 5½ pounds. Focal length of primary 19¼ inches, or f/3.2 (in combination f/13). Secondary 1½ inches diameter. A mirror of as short focal ratio as f/3.2 is usually very difficult to figure.

The following note was contributed by Harold A. Lower. "It is possible to test convex mirrors from the back, just as if the mirror were concave. The back surface of the mirror must be fairly flat and the glass well annealed, as any irregularities in the plane surface, or any strains in the glass, will appear as black lines. If not too bad, the streaks can be ignored, as they do not change with changes in the figure of the mirror. This test does not give the radius of curvature, as refraction at the plane surface shortens the apparent radius. Chromatic aberration due to refraction produces ob-

jectionable color effects, but a deep red filter (ruby glass from an old dark-room lantern) in front of the pinhole will, to a large extent, prevent this trouble. While this method of testing the secondary of a Cassegrainian does not take the place of the usual method of testing with the speculum and a large flat, it is very useful during polishing, for keeping track of the figure and preventing any very large departure from a spherical curve. The final



A 12-inch Cassegrainian-Newtonian combination made by Harold A. Lower of San Diego, Calif., with a housing which rolls off on metal tracks.

figure on the secondary mirror of a Cassegrainian, when tested from the back, will present the familiar appearance of a long-focus paraboloid, and as the figure can be seen from center to edge, it is easy to see whether it has a uniform curve. This method of testing was discovered while making a 12-inch Cassegrainian, but I have since heard that it had been reported by Ellison a number of years ago."

A note received years ago from Ellison may prove of interest. He says: "There used to be a man named Whittle, in Liverpool, who made Gregorians on what he called the 'mirror principle,' the mirrors being glass, silvered on the back and with the front surfaces worked to a curve; that of the small mirror correcting the chromatic aberration of the large one. The principle is sound. I believe he got Professor C. V. Boys to work out the curves for him. But it was too complicated. I saw one once. It might be a good stunt to set some of the 'C. P. R.' boys, who are longing for fresh worlds to conquer." ("C. P. R.," that is, Carborundum, pitch and rouge, Ellison's term for the amateur telescope maker.)

The Herschelian Telescope is favored by few. The inclination of the mirror causes astigmatism and distortion and the body heat of the observer has a maximum bad effect on the seeing, because of his position next the incoming rays of light.

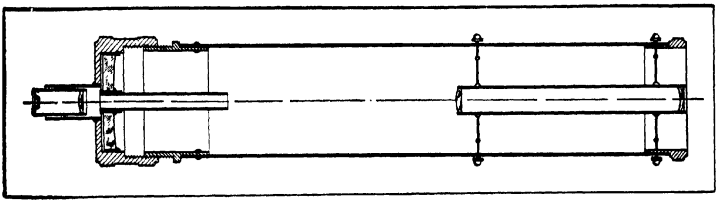
Theoretically we could dispose of that part of the distortion which is caused by the inclination of the mirror, by figuring the mirror as if it were

One of several 12-inch Cassegrainians designed by Russell W. Porter and used in the investigation for selecting the site of the 200-inch telescope. Primary focus 5 feet; e.f.l. of primary and secondary 20 feet. Duralumin mounting. Built ruggedly for mountain transportation on mule back or man back. Note rugged yoke, which is hollow. The cell is threaded and screws on. Clock drive in pier. Made by Fred G. Henson of Pasadena, California, for the California Institute of Technology.

a portion of a larger paraboloid chosen at the side, as hinted at in Wood's "Physical Optics." There are mirrors at Mount Wilson Observatory which are Herschelian in principle but their figuring was laborious. Such figuring might be done by local polishing with a sub-diameter rose tool similar to the one described in Part I, Ch. X. But would the game be worth the candle?

Captain Ainslie of England has stated that "Herschel always used single biconvex lenses as eyepieces and with these a very small displacement from the center of the field, in the proper direction, would go a long way toward correcting the image."

A combination Cassegrainian-Gregorian telescope designed and made by Ben L. Nicholson of Tacoma.

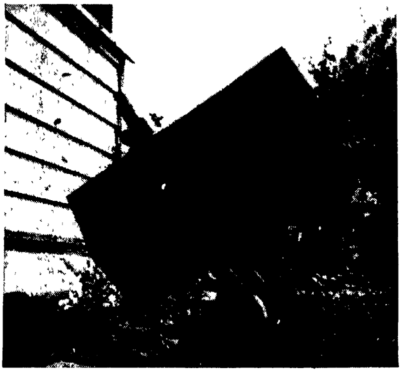


Drawing by J. F. Odenbach, after Ben L. Nicholson

Diagram of Ben L. Nicholson's Cassegrainian-Gregorian combination. The Cassegrain secondary mirror is removable.

Dewing of Diagonals or other optical surfaces sometimes occurs when the glass becomes cooler than the air; for example when the air temperature rises during the night. The remedy is to heat the optical surface involved. An old and tested treatment is the application or approximation to the surface of warmed cloths. A less transitory treatment is one used by John

H. Hindle and others, the installation of a permanent heating system. A tiny flashlight bulb, covered with tin or lead-foil (to keep in the light) is attached to the rear of the support for the diagonal and will supply enough heat and to spare, even for a large diagonal. Contrary to expectation this has not caused any undesirable temperature effects on the 20-inch mirror made by Hindle to which it was applied. Since a lamp thus closely covered may soon burn out, due to interference with its designed rate of heat radiation (just as is the case of a lamp inserted in a tube for the knife-edge test) the filament may to advantage be run at less than normal temperature by



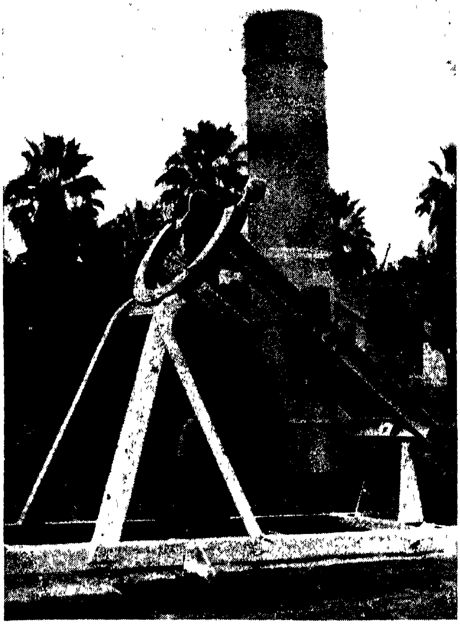
A compact, stubby Cassegrainian of f/12, with 10" × 20" tube, made by Allen K. Kirkham of Tacoma, Wash. Primary, 8", imperforate, a diagonal turning the secondary cone upward to a comfortable downward-looking eye position which never moves more than 4" and obviates the usual neck-wringing contortions of the perforated Cassegrainian. The primary, of f/2.8, was roughed out in 4 hours, while inverted over a 6" tool, mainly with 4" strokes, fine ground in 4 hours by working a small tool over it, polished in 7 hours with a 7" tool on top, and figured in 2 hours with 3" and 5" tools on top (Draper's method, which obviates turned edge). Secondary mirror 1½" diameter, 4" inside focus.

introducing resistance in series with the lamp. This method—heating with a lamp bulb—is used on the Metcalf telescope at Harvard. In general, the less heat the better.

Dewing of the main mirror seldom occurs in a reflector and is sometimes dealt with by jacketing the surrounding parts of the tube and cell.

On refractors long dew caps on the larger end of the tube may cope with dewing of the objective lens, or they may not. It is customary to warm the lens by temporarily placing warmed flannel near it. Jacketing the dewcap and end of the tube with felt is a method successfully employed by Steavenson, a less successful method being to line the dew cap with blotting paper.

High Magnification is largely a snare and a delusion. Ellison, in a letter published in *English Mechanics* (Jan. 11, 1929), refers to it as "what has been called 'the beginner's fallacy,' viz., the belief that *power* and *magnification* are synonymous. You can—if you like—put up any magnification you

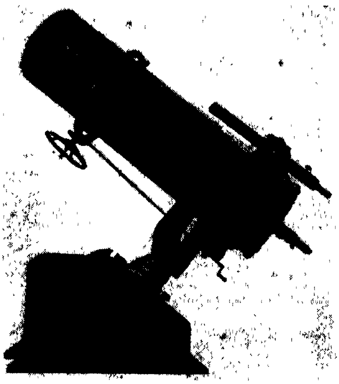


A 15-inch Cassegrainian made by Dr. H. Page Bailey of Riverside, Calif. The primary is not perforated and the secondary cone is reflected out to the eyepiece by means of a diagonal. One head of the double yoke of the mounting is depressed, enabling the tube to reach the pole of the heavens. This depressed yoke head rolls on ball bearings and is counterweighted. The framework was made from parts of a motor truck chassis. The telescope is driven by a synchronous motor.

please, on any telescope. It is only a question of getting a suitable eyepiece. It is a simple matter to rig up, for example, a compound microscope, as an eyepiece to your telescope. Such an arrangement fitted to a two-inch telescope might easily magnify 1,000 times. But what good would it do? You would not *see* any more than you would with a good Huyghenian ocular magnifying 100 times, on the same telescope.

"All experienced observers know that there is no advantage in going beyond 50 per inch of aperture, and very seldom in going up to that figure. A refractor will give you more magnification, with the same eyepiece, than a reflector of the same aperture, simply because the reflector has usually a shorter focus. If you want a huge magnification, you can get it by employing a very deep eyepiece; always provided you can find an optician who will sell you a genuine one, and that your pocket is deep enough to pay for one, if, as is likely, you have to get it made specially.

"The usual power used on the 18-inch reflector here [Armagh Observatory], for nearly all objects, is 140. Yes, actually only 140. And yet I see



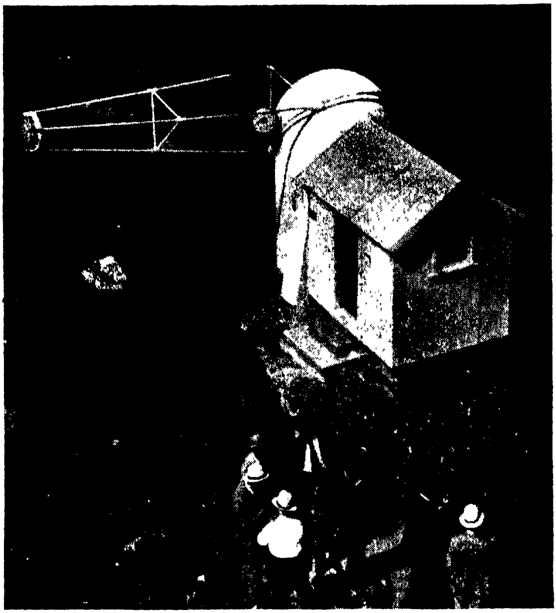
A 20½-inch Newtonian-Cassegrainian combination made by John H. Hindle and now in use in London by Dr. W. H. Steavenson, F.R.A.S., a well-known English variable star observer. The cast iron cell contains a mechanical flotation system with 18 equally loaded points. The tube is of wood. The polar axis rotates on ball bearings. The mirror, of 20.2 inches aperture, has a 5-inch perforation. Interchangeable spiders carry the diagonal for the Newtonian and the convex for the Cassegrainian. The e.f.l., when used as a Cassegrainian, is 30 feet.

far more with that than I can see with the 10-inch Grubb object-glass with 280. That does not mean that the mirror is inferior in power to the Grubb lens, but exactly the reverse. My favorite power with the Grubb telescope is 120. No real astronomer ever thinks of pushing power to its limits, unless it be for an experiment. The highest power supplied with the Grubb is only 500, and this is rarely taken out of its box; never except to split some extra difficult double star, on an extra fine night. When the books say that an extra fine lens or mirror will 'stand' 100 per inch, that only means that that power will not break down the image of a star. In other words, the image will still be a clean round dot. But I should advise the doubter to try 100

per inch on Jupiter, Mars, Saturn, or the Moon. He will not be much pleased with the result. It can be done, but the result is nasty.

"And there is one point which deserves to be emphasized with respect to refractors and high powers. *An object-glass cannot be properly corrected for all powers.* If well corrected for color in low powers, it will be over-corrected in high ones. If well corrected for high powers it will be under-corrected for low ones. A mirror is of course exempt from this defect."

Turret Telescopes: The Hartness Turret telescope (refractor) was fully and technically described, with scale drawings, in the *Journal of the American*

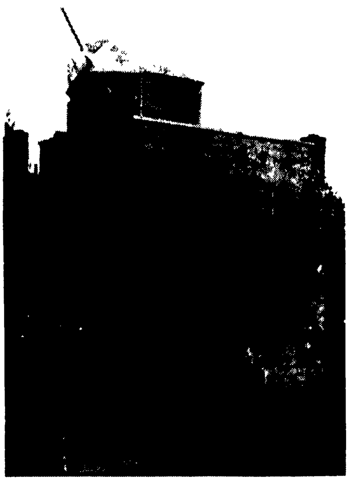


The Porter turret telescope at Stellafane, atop Mount Porter, near Springfield, Vermont. This is the instrument shown in Part I, Figure 42, at VI, but at the time the photograph shown above was taken the Cassegrainian had not been added. The turret is made of concrete.

Society of Mechanical Engineers, December 1911, pages 1511–1537; also in the *Transactions* of the same society, same year. These are on file in some large libraries. A similar turret telescope (reflector) designed and constructed by Russell W. Porter and erected by him and the Amateur Telescope Makers

of Springfield stands in front of "Stellafane" near that community in Vermont, and is shown in one of the illustrations. A turret similar in general design to the Hartness telescope is owned by J. Milo Webster, a Wyomissing, Pennsylvania, optician. A still more compact turret telescope is shown in the accompanying drawing made by the owner of the telescope, P. R. Allen, who describes it as follows:

"If the cone of rays from the flat of an ordinary Newtonian reflector be



Bonneview Observatory, constructed by J. Milo Webster of Wyomissing, Pa. The eight foot turret carries a refracting telescope mounted in a manner similar to the Hartness turret telescope.

directed down the right ascension axis, instead of out of the end of the tube as usual, and the R.A. axis be expanded until it is big enough to accommodate an observer, the result would be the working principle of my turret reflecting telescope. I obtained my inspiration and ideas for this from a description of the Hartness refracting turret telescope.

"Briefly, my scheme consists of one cast iron ring about 30 inches in diameter, mounted on a cylindrical wooden observatory, with room inside for the observer to stand. A similar ring is mounted on the first, with ball bearings between, so that the upper ring is free to rotate with its axis toward the true north. The upper ring is prevented from sliding off from the lower by a pair of ball races supported by a casting attached to the lower ring. The R.A. scale is mounted on the inside of the upper ring. It is

graduated down to intervals of four minutes. The declination circle has gear teeth cut on its periphery and these mesh with a pinion with handle attached, for ease in turning on this axis. Small electric lights illuminate the dials and my star maps.

"Entrance is from below, up ladder steps nailed to the inside of the turret. The observer stands on a little floor which can be dropped into place. Most of the work done with this telescope is variable star work using powers of 50 to 200, the latter rarely. Rocking of the telescope is noticeable with the high powers, due to the instability of the house and turret."

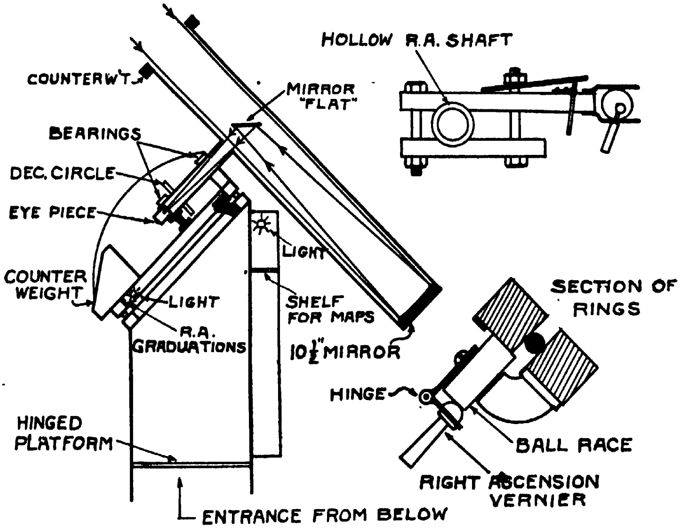
One special precaution might well be observed in connection with this type of telescope: the heavy ring should be secured in some positive manner against jumping the track, otherwise it might on some occasion slide off and do as neat a job of decapitation as a guillotine.

Inside the turret of the Webster turret telescope

For Blackening Brass the following formula has been used with success. Photographer's hypo, 8 oz., lead acetate, 4 oz., water, 2 quarts. Let the brass soak in this solution. To obtain a blue opalescent surface substitute 4 oz. of alum for the lead acetate and boil the brass in this.

Lens Design and Computation: The advanced treatises on this subject are so mathematical as to delight the dyed-in-the-wool, case-hardened mathematician but they may seem formidable to a mere human being. Southall's "Mirrors, Prisms and Lenses" is an "elementary" treatise giving much background matter. Steinheil and Voit's "Applied Optics," until recently has been a standard "headache" on the computation of optical systems, though it covers only the simple lens, but now Conrady's "Applied Optics and Optical Design" is the favorite. These books are the bibles of the first rank professional designers of high grade optical instruments. The book by Conrady, Volume I (512 pages) includes all the ordinary ray-tracing methods, the general theory of perfect optical systems, the complete theory of the primary

aberrations, and as much of the higher aberrations as is required for the design of all types of telescopes, of low-power microscopes and of the simplest photographic objectives. A second volume which is to be published will give the necessary additions to the theory largely on the principle of equal optical paths, and extend the scope of the complete work to the systematic study and design of practically all types of optical systems, with special attention to high-power microscope objectives and to anastigmatic photographic objec-



Drawing by P. R. Allen

The Allen turret telescope.

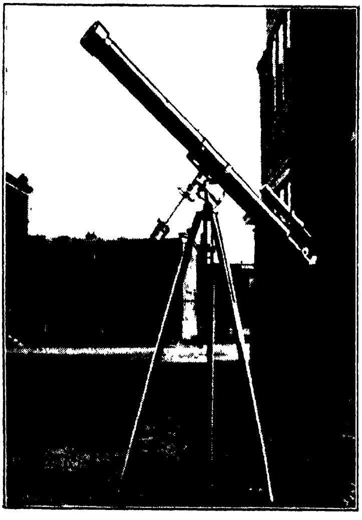
tives. The mathematical knowledge which is assumed in the book does not, as a rule, go beyond ordinary geometry, algebra, and trigonometry, but analytical geometry, and elements of the calculus are also employed in certain sections. There are 40 pages on the design of an achromatic object glass.

The May, 1917, number of the *Transactions of the Optical Society* (London) is entirely devoted to the calculation of telescope objectives. One article in this number (the one by Chalmers) is a kind of abbreviation of Steinheil and Voit's textbook mentioned above. Professor Charles S. Hastings (see Part IV), until his death America's foremost expert in design, embodied his special methods in the book, "New Methods in Geometrical Optics." These methods are difficult to comprehend and use, though they produced miracles in his hands. Letter-Circular 67 of the Bureau of Stand-

ards, entitled "Method of Designing an Objective for an Astronomical Telescope," will be of some use if one is a fair-to-middling mathematician.

There are at the time the present work is published no books on the design of microscope objectives. This job is altogether more formidable, even, than objective lens design. A designer often spends a year on one microscope lens combination, and the same is true of photographic anastigmats. Both of these are far beyond the average amateur's scope. As such design is costly, the manufacturers may be excusable because of their reticence in the matter of making available the end-products of so much labor on the part of their employed designers and computers. *The Instrument World* (London) May and June 1930, contains an article on the creation of a microscope, but the worker must be in a position to add another ingredient to it—years of experience in theory and practice on the same subject.

Literature on Practical Objective Lens Making, in contradistinction to lens designing and computing, is scarce. Fortunately, however, the best of



A 5¼-inch refractor made by Fred Caley of Frankford, Pa., from the instructions by Ellison, Part II. In order to gain general practical experience in optical work before tackling this job Mr. Caley wisely made an 8-inch reflector, a 5½-inch flat and two prisms.

the elementary material lies within the covers of the present book. If one were to hunt up all of it, Ellison's would outweigh all the other pieces in worth. It is true, not every professional worker agrees with Ellison in

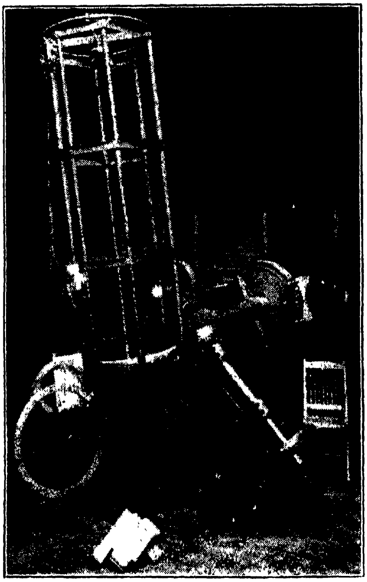
everything, but we do not all do or see things alike. J. W. Fecker, for example, writes: "I do not agree with Ellison's method of cutting lens blanks to diameter first and then grinding and polishing them. One can never get the highest accuracy of collimation by this method. The method used by all the better makers of optical instruments is to grind and polish the lens, leaving it oversize and then, after the lens is polished, to mount it on a hollow spindle so that the two images reflected respectively from the front and rear surfaces remain perfectly stationary when the spindle is revolved,

A refractor of 3 inches aperture, made by Franklin W. Smith of Glen Olden, Pa., from the Ellison instructions. Mr. Smith says: "I found that it required over four times as much work to make the three-inch refractor as to make a five-inch reflector, but the actual work is really no more difficult, assuming of course that the worker has had sufficient experience to enable him readily to produce a zone-free optical surface."

and grind each lens to its exact diameter. This is the only accurate method of getting the optical and mechanical axes to coincide. After the lens is centered to size, any necessary corrections may then be made for zonal error and so on." To this Ellison replies as follows: "I am quite aware that my way with the object-glass is not the professional way. But it works. And it is far easier than the professional way, which has the serious disadvantage, to the amateur at least, that the centering and trimming must be done after the lens is polished, to the grave peril of its surface. In my process, the centering is all done before the fine grinding is complete. It cannot be disturbed afterwards, and if there are any slight scratches, they polish out. I will back my way against the professionals, any day."

These two bits of comment are included because the amateur who aspires to make an objective lens doubtless will hear of the method first mentioned and wonder what to make of the evident discrepancy. After reading both sides of the question he will have to do his own choosing.

Other sources of information on the construction of an objective lens are "Hobbygraph" No. 3, by John M. Pierce, which contains compact instruc-



The 24-inch reflector at Yerkes Observatory, made years ago by Ritchey and described in the Astrophysical Journal, Volume 14. This picture is inserted as a study in good design.

tions for making the one-inch objective lens for a finder; a little folder sent out by Donald Sharp, which gives a short method for computing the radii of surfaces for a small objective lens, in which surfaces No. 1, 2 and 3 have equal radii and No. 4 is virtually flat; a 7-page article by Loren S. Noblitt, published in *Popular Astronomy,* May 1926, entitled "Grinding, Polishing and Correcting an Eight-inch Lens"; Bell in "The Telescope."

Literature on the Principles of Telescope Design is woefully lacking. How is it, then, that telescopes are designed at all? The knowledge of these basic principles is contained under the skullcap of a very few men and has been

acquired by a combination of putting together odds and ends picked up here and there, with gumption and experience—some of it sad. For the most part the amateur must do the same thing. A textbook on telescope design is badly needed. Why then is there no such book? One reason is that none of the mere handful of living men who are really competent to write one have seen fit to do it—perhaps for good and sufficient reasons. Another: Such a book might not pay—the demand has been too small. But that demand is now growing. A paper by E. P. Burell, Director of Engineering (telescope designer), of The Warner and Swasey Company, entitled "The Mechanics of the Telescope," appeared in *Popular Astronomy,* June–July 1931. Another entitled "Heavy Telescope Design," by Henry Simon, appeared in *Product Engineering* (New York) July 1931; this reflects the methods employed in designing Zeiss telescopes. Neither of these articles tells very much, except in a vague general way.

The Manufacture of Optical Glass and of Optical Systems is described at some length in a book of that name, which was published in 1921 by the Government Printing Office as Ordnance Department Document No. 2037. This book is a permanent record of what America learned or, more properly, taught herself about optical glass manufacture during the World War when European supplies were cut off, and after Germany had long monopolized the optical glass industry and apparently cornered the technic. Most of this work is devoted to the manufacture of glass as such.

Straie in Optical Glass are veins or irregularities whose refractive index is a little different from that of the surrounding glass. Their understanding, detection and so on are described in Scientific Papers of the Bureau of Standards No. 373, "Characteristics of Straie in Optical Glass," to be had only from the Government Printing Office, Washington, D. C., price 5 cents. (Postage stamps in payment are not accepted by the Government.)

Strains in Glass, and Their Detection: Poorly annealed glass often refuses to hold its figure and causes trouble. Advanced workers, before beginning operations on large disks, may wish to test them for possible strain. Bell devotes a page to this subject, and the following extract may assist. It is from an article entitled "The Annealing of Glass," by A. N. Finn, Chief of the Glass Section at the National Bureau of Standards. This was published in the *Journal of the American Ceramic Society* (Columbus, Ohio), August 1926, and is extracted by permission:

"The rapid reduction in the temperature of glass which is incident to practically all commercial molding almost invariably produces a condition in the glass commonly known as 'strain.' (This is permanent strain and should not be confused with temporary strain resulting from the application of external force or temperature differences.) This condition must, in general, be removed before the ware is satisfactory for commercial purposes and its removal is called annealing or tempering. (Tempering sometimes means the intentional introduction of strain, as, *e.g.,* in the heat treatment of glass to produce special physical properties.)

"Strain is due to an inelastic yielding under the stresses developed within

the body of the glass while cooling, because at any moment during this time the different parts of the body are not contracting at the same rate. During molding the surface of the hot glass, coming in contact with the relatively cold mold, shrinks or contracts very rapidly and is quickly cooled to a temperature at which the glass is rigid. The interior loses its heat more slowly and, consequently, contracts less rapidly than the surface which must, therefore, if the stresses become large enough, either crack or yield inelastically.

"After the surface becomes rigid or at least practically so, it does not yield readily to any force applied to it and tends to resist the contraction of the hotter and relatively soft interior as it continues to cool and contract. This produces stresses in the glass, the surface usually being compressed while the interior is dilated. If these stresses exceed the strength of the glass, it will break. This may occur either during the initial cooling or subsequently whenever the glass is subjected to sudden temperature changes, such as those resulting from the action of hot or cold water. In order to reduce the liability of breakage of ordinary ware to a minimum, glass must be annealed.

"The annealing of glass consists of two fundamental steps. The first is to heat it to such a temperature that the entire body of the glass becomes sufficiently soft to permit it to yield. Then, if sufficient time be allowed, the stresses developed during molding will disappear. The second is to cool it so slowly that the temperature differences between the interior of the glass and its surfaces, with the consequent differences in contraction, are not great enough to produce objectionable strain.

"Strain in glass is easily detected by means of polarized light. A beam of light (white light) is either reflected from or passed through a 'polarizer' which in the first case is usually a plate of black glass or, in the second, a number (pile) of thin transparent plates, and in both cases the surfaces of these plates must make a definite angle with the beam. The reflected or transmitted beam then passes through the sample being tested and is again reflected at the same angle as before from another plate of black glass or is passed through a second pile of plates set at the proper angle. In either case these are called the 'analyzer' and they are sometimes replaced by a nicol prism. From the character of the light finally passing the analyzer the degree of annealing is determined. If the sample is free from strain, no change in the intensity of the field (as compared with the field when no sample is used) or in the appearance of the sample will be observed; if it is moderately strained, the light will be brighter in certain areas; and if it is highly strained, it will appear colored, and the color will vary over the field of view.

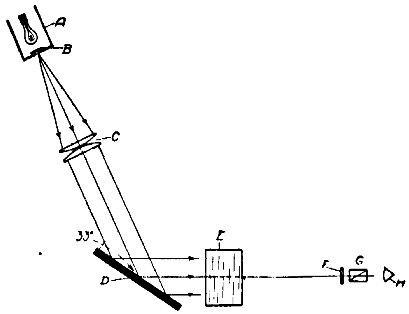
"If the analyzer is a nicol prism, a sensitive tint plate may be advantageously used because this, in a way, intensifies the effects obtained with moderately strained glass by producing a series of colors which can be more easily interpreted and compared with those obtained in testing other (standard) samples.

"The apparatus used at the Bureau of Standards for determining the 'amount of strain' or the degree of annealing is so simple in construction

and yet so eminently satisfactory that a detailed description of it will be given. (See figure.) A 200-watt electric light bulb is enclosed in a box made of bright sheet metal. A ½-inch hole is cut in one side of the box and covered with a piece of glass whose surface is 'fine' ground. This small piece of glass, illuminated by the lamp, is the actual source of light.

"A condensing lens, 7 inches in diameter and having a 15-inch focal length, is so placed that its focus is at the 'source of light.' The light after passing through the lens is practically a parallel beam, but not entirely so since the source is not a 'point.'

"The beam of light then strikes a piece of polished black glass at an angle of approximately 33° (between the beam of light and the glass) or the angle which is necessary with the particular glass for obtaining the best



***Sectional** view of polariscope for testing glass for strain A, source of **illumination**; B, ground glass, C, condensing lens, D, black glass plate (polarizer); E, sample to be tested; F, sensitive plate; G, nicol prism (analyzer); H, observer's eye.*

polarization possible. (An angle of 33° can easily be obtained as follows: Draw a right triangle with one side 15¼ inches and the other side 10.0 inches long. The angle between the long side and the hypotenuse will be about 33°.) Although the beam of light reflected from the black glass is apparently not affected, it is, nevertheless, polarized.

"At some distance in front of the black glass polarizer a nicol prism is placed in the polarized beam, so that the enlarged image of the 'source' is visible through it. By turning the nicol, the intensity of the light will change progressively from bright to dark. The nicol is properly set when the field is as dark as possible.

"The tint plate, which should be a 'First Order Purple' (retardation, about 575$\mu\mu$), is mounted directly in front of the nicol prism and is set by turning it until the color of the light passing through the prism is as marked as possible. Nicol prisms and tint plates can be obtained from practically any dealer in optical instruments.

"If, now, a piece of strained glass is placed in the beam of light between the polarizing plate and the nicol, parts of the glass will apparently be colored differently than the original field. If well-annealed glass is examined, practically no change in color will be seen and if a highly strained piece of glass is used, the colors will be vivid. If the tint plate is removed and the same pieces of glass are examined, the first (moderate strain) will appear brighter in certain areas, the second (no strain) will produce no change, and the third (high strain) will be very bright or even colored in some places.

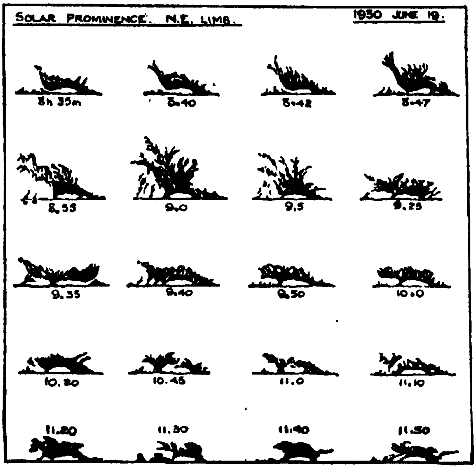
"Glass being tested should be absolutely uniform in temperature. Ware taken from a room warmer or colder than the room in which the testing is done will show different amounts of strain than if allowed to come to thermal equilibrium. Even the effect of the heat from an inspector's hand will be pronounced, especially if the ware is thick."

[EDITOR'S NOTE: The seven-inch condensing lens of 15-inch focal length which the author mentions is the kind used in the particular apparatus at the Bureau of Standards, but almost any available equipment which will produce enough parallel rays over a sufficient area will serve relatively well. The head light or spot light of an automobile could be used as a source of light. Also, a piece of black glass for the polarizer is not essential, as a thin piece of polished plate or machine drawn window glass will serve quite well. The nicol prism may be purchased from a dealer in laboratory supplies, such as the Gaertner Scientific Corporation of Chicago or the W. M. Welch Scientific Company of the same city, and need not cost more than a few dollars. A small size, say 6 mm., will suffice. Bausch and Lomb of Rochester, New York, can furnish nicol prism and tint plates. The black glass may be obtained from the Pittsburgh Plate Glass Company, Pittsburgh, Pa., or their agencies, also from the Vitrolite Company, Parkersburg, West Virginia.]

Import Duty on Optical Apparatus: The Tariff Act of 1930 states that telescopes and parts are dutiable at 45 per cent *ad valorem;* for exhibition, free (this is not freely construed in practice, but rather closely). Glass for optical instruments or equipment or optical parts, scientific or commercial, is dutiable at 50 per cent. Mirrors for optical purposes 45 per cent. Owing to the changing vicissitudes of politics it may be well, before going very far toward importing optical materials, to check up on these or similar data by writing the Treasury Department at Washington, as tariffs have a way of changing. The services of a customs broker in New York to steer the matter through mazes of red tape are likely to prove worth while. These services cost about five dollars and the brokers understand the red tape. Duty on small articles sent by mail is collected at the local post office.

Literature on the Spectroheliosoope: A series of papers by Hale, entitled "The Spectrohelioscope and its Work," appeared in *Astrophysical Journal:* Part I, (*i.e.,* the first paper) History, Instruments, Adjustments and Methods of Observation, in Volume LXX, pages 265–311, 1929 (reprinted as "Contributions from the Mount Wilson Observatory," No. 338); Part II, The Motions of the Hydrogen Flocculi Near Sun-spots, in Vol. LXXI, same,

pages 73–101, 1930 ("Contribs. Mt. W. Obs.," No. 393); Part III, Solar Eruptions and Their Apparent Terrestrial Effects, in Vol. LXXIII, same, pages 379–412, 1931 ("Contribs. Mt. W. Obs.," No. 425); Part IV, Methods of Recording Observations, in Vol. LXXIV, same, pages 214–222, 1931 ("Contribs. Mt. W. Obs.," No. 434). Some of the same matter was more



Evolution of a solar prominence, as seen and sketched at intervals between 8:35 and 11:50 on the same morning, by F. J. Sellers, F.R.A.S. Reproduced from the Journal of the British Astronomical Association. The maximum height at 9 A.M. was 30,000 miles, the velocity of ascent having been 12 miles per second. Effects similar to these may be watched through the spectrohelioscope. More rarely, solar prominences reach a height of 200,000, 300,000, or even 500,000 miles.

briefly dealt with by Dr. Hale in *Nature* (London), Sept. 18, 1926; May 14, 1927; April 28, 1928.

Replica Gratings of Sufficient Size, resolving power and brightness, are not yet available for the spectrohelioscope. Numerous attempts to perfect the process of making large replica gratings have not, as this book goes to press, produced satisfactory results. Those interested in conducting further research on the problem should first consult an article by Dr. J. A. Anderson of the Mount Wilson Observatory, in *Astrophysical Journal,* 1910, pages 171–174. See also a footnote in Chapter II of Part IX regarding the electrolytic process. This effort was made by Mr. B. Bart of the Bart Laboratories, Newark, N. J., who intends to continue his experiments.

Ruling Engines for Making Diffraction Gratings: A few amateurs have attempted or planned to make ruling engines, a most ambitious feat. There

is little literature on this subject. Probably the best practical article is by Dr. J. A. Anderson of the Mount Wilson Observatory, in Glazebrook's "Dictionary of Applied Physics" (Macmillan), Volume IV, pages 30–41. There is also a hint or two in Michelson's "Studies in Optics." Ruling engines demand extreme precision in workmanship, and the patience of Job when it comes to their later adjustment. After making and adjusting them, it is necessary to learn to live with them. Here is what Michelson said concerning them: "One comes to regard the machine as having a personality—I had almost said a feminine personality—requiring humoring, coaxing, cajoling, and even threatening! But finally one realizes that the personality is that of an alert and skilful player in an intricate but fascinating game who

Albert A. Michelson.

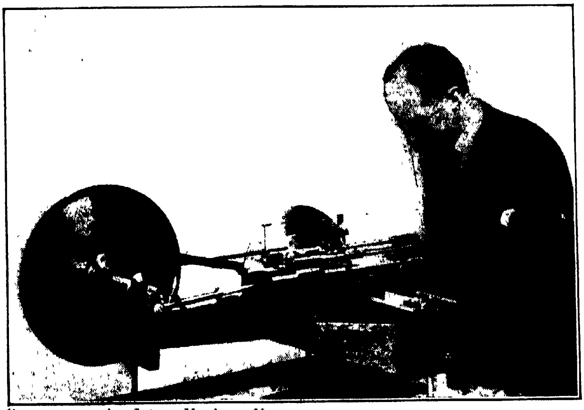
One thread—a strong flair for extreme precision—ran through all of Michelson's work in science.

will take immediate advantage of the mistakes of his opponent, who 'springs' the most disconcerting surprises, who never leaves any result to chance, but who nevertheless plays fair, in strict accordance with the rules of the game. These rules he knows, and makes no allowance if you do not. When *you* learn them, and play accordingly, the game progresses as it should."

Dr. Karl K. Darrow of the Bell Telephone Laboratories, in one of his monographs on "Contemporary Advances in Physics," says: "The ruling of good gratings is an art; and those who have practiced it with conspicuous success are fewer far than those who have attained preëminence in music or

in painting. Amateurs, mechanics, and professors figure upon the list, the first of all being Fraunhofer, who from a glazier's apprentice evolved into the founder of spectroscopy. After his gratings of wires and of scratches in a foil of gold-leaf, he invented the method of engraving with a diamond-point upon a surface of metal or of glass (he used the latter) which is followed to this day. He met and grappled with all the difficulties which were later to beset his followers, and described them in language which now sounds strangely modern. Then, as now, it was possible to rule tens of thousands of rough grooves roughly to the inch; the trouble lay, as still it lies, in making them identical and spacing them equally.

"Equality of spacing depends upon a screw, which is turned through a prearranged angle and is expected to advance through a definite distance



Courtesy of the Johns Hopkins University

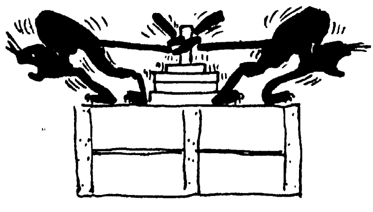
Professor Henry Augustus Rowland (1848–1901) with his famous ruling engine. Chief credit for developing the ruling engine belongs to Rowland, who in the early Nineties turned out gratings ruled with 14,000 to 20,000 lines per inch, which became famous in laboratories the world over.

carrying the future grating with it, whenever the diamond has completed one ruling and is waiting to begin the next. Screws as manufactured are not good enough; and anyone who aspires to be a maker of gratings must first of all procure the best available, and then devote a long and tedious time—literally years—to making it still better. Primacy in the art passed to America in the eighties of the last century, because Rowland of Johns Hopkins developed with much labor a process for removing, or at least for mitigating, the imperfections of a screw. The greater the number of rulings to be laid down side by side, the longer the portion of the screw which must be made, as nearly as humanly possible, perfect; and Michelson has testified, from unrivalled experience of many years, that the time required for the

process varies as the cube of the length of the screw and width of the planned-for grating. Increase of resolving-power thus is bought at an enormous price in patience and in perseverance. A research institute is as proud of a notable grating by Rowland or Michelson or Wood, as a picture gallery of an authentic Titian or Velasquez; and the promise of a new talent is not more joyfully received, than a rumour that someone is working to perfect a yet longer screw to make a yet wider grating.

"Alikeness of successive rulings depends on the endurance of the diamond. The ruling-engine is sequestered in a well-insulated room, and after the temperature has settled down to constancy is set in motion by some device worked from outside, and left to do its task in solitude. If the diamond breaks, or suffers any great change in shape during the operation, the grating is good for nothing. This cannot be foreseen, it is not even known when it happens; to stop the process to see how things are going would be like digging up a seed to see how it is sprouting. The chance of such an accident is naturally greater, the more numerous the lines—another obstacle to the successful ruling of many-lined gratings of high resolving power."

Here, then, is a supreme job for brave amateurs to tilt with—make a ruling engine and make it perform well. So far as is known, the only ruling engines in this country are the original Rowland engine and one or two others at the Johns Hopkins University, used by Professor R. W. Wood assisted by Wilbur Perry, formerly of the Telescope Makers of Springfield, Vermont; The Michelson engine at the Ryerson Laboratory of Physics, University of Chicago; an engine at the Pasadena laboratories of the Mount Wilson Observatory; one at Cornell University, Ithaca, N. Y.; and one or two others for ruling coarser gratings. There is one at the National Physical Laboratory at Teddington, near London, England.



BOOKS FOR THE AMATEUR ASTRONOMER

If the present volume opens the worker's way to the study of astronomy, and thence possibly to that of the other sciences, it will have served doubly well. In such an event it may later become the nucleus of an astronomical library, a special six-foot shelf.

In the following section a number of books are briefly described. This list does not name all the books; it is a selection.

Books on light, physics, etc.: The Editor is frequently asked to recommend a book on light. There are many, but rather than try to name them all a few are chosen with a view to their suitability. For the beginner: Sylvanus Thompson's *Light—Visible and Invisible.* This is a stenographic transcript of a series of popular lectures illustrated by means of apparatus, and the reader will feel that he is actually present at the lecture. *Physical Optics* by R. W. Wood, Professor of Experimental Physics at Johns Hopkins, is the last word on this subject, but it is primarily for advanced students who know higher mathematics. It is exhaustive (700 pages), but the larger part of it could be followed by the "graduate" from *Light—Visible and Invisible,* named above. It is interesting to note that Professor Wood is himself something of an "amateur" telescope maker and that he has followed with interest the recent popularization of the work; it was he who constructed the revolving dish of mercury telescope, mentioned elsewhere. Edser's *Light for Students,* might to good advantage form an intermediate course between the two books named above, for the ambitious home student. It is a 580-page work involving nothing worse than high school mathematics. Other books which fall outside this suggested course of study are *Light* by Prof. C. S. Hastings of Yale, an elementary treatise of great lucidity (out of print); *Light Waves and Their Uses,* by Prof. A. A. Michelson, also his *Studies in Optics* (1927); *Physics of the Air,* by Prof. W. J. Humphreys, Chief Physicist of the U. S. Weather Bureau, which will explain many phenomena bearing indirectly on observation, seeing, atmospheric optics, etc., for the advanced amateur. In the latter connection, an article in *Popular Astronomy* for June, 1897, by Prof. A. E. Douglass, entitled *Atmosphere, Telescope and Observer,* will prove instructive concerning the causes of bad seeing.

To get a straight physics textbook treatment of light and optics, Knowlton's *Physics for College Students* is highly recommended. The book is unusually non-mathematical and is less "textbookish" than most texts, and more suitable for use where one cannot pursue the course in a regular class. Incidentally, it takes up the new physics of the atom; Einstein; space, time, gravitation; etc., and is the book The Editors of the *Scientific American* recommend to nearly all inquirers for a good physics text.

The Amateur's Telescope by Ellison is the original, published in England, from which Part II. of the present work was reprinted. It contains a few things not included in the present volume. A number of advanced amateurs have obtained it in order to have the original.

Bell—The Telescope: The average amateur will waste a lot of time and thought unless he possesses himself of a copy of Bell's invaluable 287-page work, *The Telescope*. Some of the many subjects treated are: early telescopes, optical glass and its working, testing glass; objective lenses; mountings, including several that are more or less unorthodox; eyepieces, their optical principles; binoculars; accessories such as star diagonals for easy zenith observing, polarizing eyepieces, ring and filar micrometers, clock drives, spectroscopes, diffraction gratings, the spectro-heliograph, photometers; the care and testing of telescopes, with various distorted star images and what they reveal about an objective lens under test; how to clean a dirty objective lens; lacquering mirrors; silvering; how to put a telescope into the meridian; housing and observations; resolving power, what it is and why; and a brief course in microscopy. No "how-to-make-it" instructions are given, but the advanced amateur should not try to keep house without this book which fills in the whole general background on telescopes and their underlying principles.

German Telescope Books: For those who like to read German there is a little book entitled *Selbstherstellung eines Spiegel Teleskops*, by Prof. Dr. A. Miethe, published by Franckh'sche Verlagshandlung, Stuttgart, Germany, second edition 1921. *Das Moderne Spiegelteleskop in der Astronomie*, by von Krudy, revised 1930 by Prof. Brunn, published by Johann Ambrosius Barth, Leipzig, contains 50 pages on practical mirror and telescope making.

Mirrors, Prisms and Lenses, by Southall, is a full, general treatise on applied optics and includes the theory of lenses, etc., but contains nothing on practical work. It is somewhat mathematical. A standard work.

Fath's *Elements of Astronomy* is a remarkably lucid textbook suitable for the beginner. It is not a large book—328 pages. The author has a knack of stating things in such a manner that one can get hold of them easily and carry away the main impression without becoming involved in the secondary details. At the other extreme in length is the new Russell, Dugan and Stewart *Astronomy*, in two volumes, 962 pages, "the most complete astronomy in the English language," yet not on this account abstruse or beyond the intelligent beginner's depth. Volume I, which may be purchased separately, treats of the astronomy of position and the solar system; Volume II treats the stars and embodies a 50-page treatise on astrophysics. Neither volume is mathematical, but parts of Volume II will require some knowledge of physics. Nevertheless, if The Editor were permitted to recommend but one book from the whole field of astronomy it would be this one. Although the volumes are splendidly produced the price is remarkably low. Intermediate in length between Fath's textbook and Russell, Dugan and Stewart's textbook is Prof. J. C. Duncan's *Astronomy*. This is a 380-page college textbook, mainly nonmathematical, and is very compact and full of information. It has been very favorably received by teachers of astronomy.

The Fundamentals of Astronomy, by Mitchell and Abbot, has been described as "a cross between a textbook and a popular treatise"; it is a textbook without the earmarks of a textbook—a sort of "tamed," humanized textbook.

Stetson's Manual of Laboratory Astronomy is used in first year college courses in astronomy, in connection with class work and actual observation. It outlines plenty of tasks for those who wish to knuckle down to systematic work.

Stetson's *Sky Map Construction for Everybody* is a 28-page booklet and is a reprint of parts of Stetson's *Manual of Laboratory Astronomy.* It will teach in a most practical way all the main constellations.

The New Heavens, by Dr. George Ellery Hale. Until about twenty years ago, astronomy was simply a more or less cut-and-dried member of the several sciences. Nearly all of the new birth of astronomy has had to do with the stars instead of the planets. Dr. Hale's book gives the reader a clear concept of what all this rebirth signifies, and gives it in popular language.

Todd's *New Astronomy* is particularly recommended, not to those who wish to study the newer developments of stellar astronomy and astrophysics but the ordinary astronomy of position, the movements of the heavenly bodies and similar astronomical commonplaces which usually baffle the beginner for some time. In making these things clear Todd's homely, detailed explanations are in a class by themselves. Some of the illustrations are somewhat old, but still they explain more clearly the points involved than any The Editor has seen, and where the amateur is forced to work alone instead of in a class room with other students and a teacher, this consideration always becomes important. He is likely then to discover himself hunting up his good, old-fashioned Todd, when after reading elsewhere the explanation of a given fact, he is still "as clear as mud" about it and is accusing himself of being "thick."

Astronomy, An Introduction. By Robert H. Baker. Intended for use in introductory college courses. A 500-page textbook covering the subject in thorough systematic manner. Has been well received.

Astronomy. By F. R. Moulton. This is a new book (1931), not a mere revision of the earlier text by the same author. Many regard it as the most readable of all the elementary textbooks. It is perhaps best adapted to the needs of the outside reader. Moulton never is dull. He devotes a larger proportion of the 583 pages of the book to the simpler things within the solar system than most authors, and less to the cosmological and astrophysical aspects of the science.

The Sun. By G. C. Abbot. A standard treatise revised and once more made available. It treats the following aspects of its subject: the solar system; instruments used in solar investigation; the photosphere; eclipses and the outer solar envelopes; sun-spots, faculae and granulation; what is the sun; the sun as the earth's source of heat; sun's influence on plant life; utilizing solar energy; the sun among the stars.

Meteors. By C. P. Olivier. The standard treatise on meteors. 278 pages.

Comets. By C. P. Olivier. The standard treatise on comets. 239 pages.

Flights from Chaos. By Harlow Shapley. A noteworthy attempt to systematize everything from electrons to the metagalaxy. 166 pages.

Man and the Stars. By Harlan T. Stetson. A popular work which ex-

plains astronomy by taking the reader through the history of its development. The explanations of each advance are lucid. 216 pages.

The Mysterious Universe. By Sir James Jeans. A readable cosmology dealing on a grand scale with the greatest concepts. This book has almost broken the best seller record for scientific books. 160 pages.

The Universe Around Us. By Sir James Jeans. Covers modern astrophysics and cosmological concepts in a semi-popular way. It, too, has enjoyed a deservedly large sale. 331 pages.

Opticks. By Sir Isaac Newton. An exact modern reprinting of Newton's immortal work, except in modern type. Genuine originals of the same work cost about 20 dollars at second hand.

A Manual of Celestial Photography. By Prof. E. S. King of Harvard. This book contains the practical results of its author's whole lifetime of specialization in astronomical photography.

A Source Book in Astronomy. By Shapley and Howarth. The most notable passages selected from the actual writings of the greatest astronomers, from Copernicus to modern times, assembled and reprinted in a single volume.

The Internal Constitution of the Stars. By A. S. Eddington. A study of the mechanical and physical conditions in the deep interior of the stars. This book is largely mathematical. 402 large pages.

Lens-work for Amateurs. By Henry Orford. Contains a considerable volume of practical matter available to the builder of optical instruments, as seen by an actual shop worker. Of this there is little on telescopes as such, but much bearing on eyepieces and much else that will enlarge any practical worker's general background.

Dictionary of Applied Physics. By Sir Richard Glazebrook. Contains several articles which will be of much value and interest to workers capable of dealing in terms of physical and geometrical optics, and in some measure to all—to wit: On diffraction gratings, theory, manufacture and testing, 23 pp.; precision dividing engines for circles, 6 pp.; eyepieces, 6 pp.; glass, 30 pp.; interferometers, 6 pp.; microscope optics, 35 pp.; testing compound objectives, 8 pp.; optical calculations, 28 pp.; optical glass, 10 pp.; working of optical parts, 22 pp.; photographic lenses, 14 pp.; polarized light, 20 pp.; spectroscopes, 32 pp.; the telescope, 22 pp. This reference encyclopaedia of five large volumes costs about $75, but amateurs may sometimes consult it in large public libraries, university libraries, laboratories and so on, as it is a standard work which is widely known to physicists and other men of science.

Splendour of the Heavens. Composite authorship by 19 members of the British Astronomical Association. This book is accurately described as "a popular authoritative astronomy." It is a big book, 8 pounds, 9 x 11 x 2 inches, containing 976 text pages and 1129 illustrations. More than the plain textbooks on astronomy do, this book treats of things within reach of the average amateur's telescope. Captain Ainslie's contribution, pages 712–765, "The Amateur at Work," is mainly about telescopes and was written by a man who knows telescopes, not as an arm-chair or closet student but from years of immediate familiarity with them. Pages 835–878 contain a sectional

reproduction of Goodacre's 60-inch map of the moon, with accompanying descriptive matter. A good star atlas with R.A. and Dec. of feature stars, etc., follows this. This great book has had an exceptionally wide sale among amateur astronomers, and deservedly so. Its authorship is a sufficient guarantee of its accuracy and it is a perfect mine of information.

Field Book of the Skies. By Olcott and Putnam. A practical handbook for out-of-door star gazers. Each constellation is taken up, first for the naked eye and for field glass, then for telescopes; also for its mythology. This book also contains much other odd lore of astronomical interest and is recommended for use with telescopes not equipped with setting circles. 516 pages. Hip pocket size.

Elements of Practical Astronomy, by Dr. W. W. Campbell. After the amateur has mastered descriptive astronomy, he may want to dip into celestial mechanics and see why the heavenly bodies act as they do. If he has had a previous speaking acquaintance with trigonometry, this standard textbook will be invaluable for this purpose. *Introduction to Celestial Mechanics,* by Moulton, resembles in scope the book last mentioned, except that it is more lengthy and more complete. It also requires previous work in higher mathematics.

Chauvenet's *Manual of Spherical and Practical Astronomy* is a two-volume work used by all astronomers. It is almost wholly mathematical. Volume I is devoted to the mathematics of astronomy, Volume II to applications of the same mathematics and descriptions of instruments. If you find the most hard-boiled textbooks becoming tame, and want something *solid* to chew on, Chauvenet is the very last word. It is a true *pièce de résistance.* It is not a new work, but this sort of thing never gets out of date, anyway.

Textbook on Spherical Astronomy. By W. W. Smart of Cambridge University. Amateur astronomers with mathematical leanings will revel in this new book, which fills a gap that has previously been but poorly filled. It covers in separate chapters: spherical "trig," the celestial sphere, refraction, the meridian circle, planetary motions, time, heliographic coordinates, aberration, parallax, precession and nutation, proper motions, astronomical photography, navigation, binary star orbits, occulations and eclipses, and is almost wholly mathematical; 408 pages.

Mathematical Astronomy. By Barlow and Bryan. An elementary treatise which might well precede the study of Campbell, Moulton or Chauvenet in the same field.

American Ephemeris and Nautical Almanac. This old stand-by of the practical astronomer will become a necessity as soon as the amateur has mounted his telescope equatorially and put it into accurate adjustment with the earth's axis. From this time on, he can look up the desired star in the Ephemeris, set the circles on his telescope, look through the eyepiece, and the star is there! The Ephemeris gives the places (celestial longitudes and latitudes) of the Sun and planets for every day, the Moon for every hour and some 800 of the brighter stars; it also gives elements of all Moon-star occultations (stars eclipsed by the Moon), eclipses for the year, and those of the satellites of the planets—all published several years ahead. An abridged edition, plenty detailed enough for most of us, is also available.

Eclipses of the Sun, by Mitchell, is a standard work of large size. *Stars of the Southern Skies,* by Orr, will interest our Australian, South African, Argentinian and Chilean amateurs.

Starlight, by Director Shapley of Harvard Observatory, is an excellent, brief treatment of modern astronomical discoveries.

A Beginner's Star-Book, by Kelvin McKready, is well suited to the amateur, whether he has a telescope, opera glasses or eyes alone. Some chapters are: Learning to Observe; Star Maps for Any Year; Objects to be Seen; Catalog of Interesting Stars, etc. It contains a map of the Southern Skies. Pages, 150; large size.

Astronomy With an Opera Glass, by Garrett P. Serviss. A book which has stood the test of time. There are many books on this general aspect of astronomy. This is still one of the best.

The Friendly Stars, by Martha E. Martin. There is a steady demand for books that weave poetic feeling in with fact. Of this class of books, the above is a worthy representative. It is a naked eye star book.

Celestial Objects for Common Telescopes is a recent edition of a well-known work by Webb. There are two convenient sized volumes. The most useful feature is a rather detailed list of double stars and other showpieces of the heavens which an amateur whose telescope is equipped with adjusted setting circles will want to find. Goodacre's 22-inch Moon map is included.

A Guide to the Constellations, by Barton and Barton, will perhaps suit the average beginner better than any other atlas. Its maps are especially clear, in contradistinction to some maps which show so many things that the unaccustomed tyro is confused by them. The book is devoted exclusively to naked-eye, observational astronomy. One thing noted with gratitude is, that the pronunciation of each constellation and star is given, a boon to the isolated student. In addition to maps there is ample discussion of each heavenly feature.

Star Atlases: Upton's and Norton's star atlases are the two which are most used in schools. Norton's atlas was brought up to date in 1927 and in our opinion is the best available atlas for advanced amateur use. It is a large, thin volume with the emphasis on the contents rather than on physical appearance. The 17 large maps show 7,000 stars (six magnitudes) nebulæ, clusters, etc. The first half of the book is a sort of general compendium of practical star information and is as crammed full of facts as a Christmas pig. Ball's *Popular Guide to the Heavens,* an old standby which was brought up to date in 1926, is a thicker volume of smaller dimensions than Norton's and is notable as an example of fine book production. The thick chart paper and the 86 beautiful blue charts and illustrations make it a book to admire as well as use. *The Pathfinder Star Maps,* by Prof. Edward S. King, of Harvard, is a booklet containing charts similar to those published in the *Scientific American,* except a little larger and with explanation.

Moon Maps, Astronomical Pictures, etc.: No doubt more beginners become interested in the endless details of the Moon's surface than in any other object

of the heavens, and The Editor therefore receives frequent queries for Moon maps. An 18-inch map by Elger may be secured from the Eastern Science Supply Company, dealers in charts and other astronomical equipment, for two dollars. Goodacre's 24-inch Moon map forms a part of Webb's Celestial Objects for Common Telescopes, 6th Edition (described above). Walter Goodacre has also published a 60-inch map, both separately (out of print) and in the *Splendour of the Heavens*. H. P. Wilkens has made a 200-inch map, published in sections each measuring 22 x 30 inches. A photograph of a drawing of the Moon, 7 inches in diameter, by Porter, may be had from Yerkes Observatory; see also moonscape sketches in *Popular Astronomy*, October, 1916. A special collection of memoirs on the Moon may be purchased at very reasonable expense from the *British Astronomical Association*; send for list of published memoirs on Sun, Moon, planets, etc. Yerkes Observatory has for sale a large collection of astronomical photographs, lantern slides and transparencies. The prices put them within reach of most amateurs. Address the University of Chicago Press, Chicago, Ill. Photographic prints, especially of the Moon, may also be purchased from the Mt. Wilson Observatory, Pasadena, Calif. Unmounted prints cost about fifty cents apiece, most of them are extremely beautiful and are fit for framing. There is a very good 24-inch Moon map drawn by Karl Andel and reproduced by V. Neubert and Synové, Prague XVI, Czecho-Slovakia. It shows all the formations under rising Sun illumination.

1001 Celestial Wonders is a new book by the amateur telescope maker Charles Edward Barns. This is the best book we know for the amateur whose telescope is equipped with setting circles, because he can make with it a systematic canvass of the heavens, since each chart blocks off a small area and the text opposite tells what to look for in it. Pocket size. Part II is on instrument making, including reflector and refractor, eyepieces and small spectroscopes.

A Photographic Atlas of Selected Regions of the Milky Way is unique; its charts are *actual photographs*, 51 of them, each 9 inches square, taken with the Bruce Photographic Telescope by the late venerated Professor Barnard. This two volume set is most suitable for the amateur who wishes to make a detailed study of the peculiarities of the Galaxy, rather than as a star atlas. Each photograph is explained in detail. A beautiful work.

Other Literature. Draper's original paper on "The Construction of a Silvered Glass Telescope, Fifteen and a Half Inches in Aperture," and Ritchey's paper, "On the Modern Reflecting Telescope and the Making and Testing of Optical Mirrors," appeared in the *Smithsonian Contributions to Knowledge*, Volume 34, 1904. This volume is out of print but may be consulted in some libraries. Both papers were reprinted in the *Scientific American Supplements*, the Ritchey paper appearing first (December 24 and 31, 1904 and January 7, 14 and 21, 1905), and the Draper paper July 29 and August 5, 12 and 19, 1905. These Supplements are not available except in some public libraries. The Rev. C. D. P. Davies published an article on the testing of

paraboloidal mirrors, in *Monthly Notices of the Royal Astronomical Society*, March, 1909; "The Poor Man's Telescope" (*i.e.*, the reflector) by R. W. Porter was published in *Popular Astronomy*, November, 1921 (out of print); also see "Knife-Edge Shadows" by the same author, *Astrophysical Journal*, June, 1918 (out of print). "The Polar Reflecting Telescope" by R. W. Porter appeared in *Popular Astronomy*, May, 1916. "The Enclosed Observing Room," by the same author, was published in *Popular Astronomy*, May, 1917, and reprinted in *Scientific American Supplement 2170*, which is not, by the way, obtainable from the *Scientific American;* try the H. W. Wilson Company, dealers in old issues, who still have certain of the Supplements left in stock.

SOCIETIES

Astronomical Societies: As an added incentive to persistence on the part of the new worker to hang on when things are going wrong and when there is perhaps an inclination to chuck over the whole job, there are two interesting scientific societies into which almost any amateur with serious intentions and a telescope is welcomed; the *American Association of Variable Star Observers* (A. A. V. S. O.) and the *American Meteor Society*. With regard to the former the situation is this: professional astronomers would like to keep close watch on a large number of stars which vary in brightness over certain periods of time. To perform this work for science there are not, however, enough professionals to go around. The A. A. V. S. O. was therefore organized with a large share of its membership among amateurs, and its sponsors state that the association stands ready to help new workers with charts, blanks and instructions. Annual membership is two dollars. At present something under 100 active observers carry on the work and their reports are regularly published in *Popular Astronomy*.

The other organization, the *American Meteor Society*, welcomes to membership all persons who are interested in astronomy. Personal application should be made. (See Directory.) Dues are one dollar. All who are using moderate sized telescopes are urged to keep a record of telescopic meteors seen by them in the course of their observation. Blanks and instructions will be sent free on application, and without obligation to join unless one wants to. Members also secure and transmit data on large fire balls, photograph meteors, etc.

The editor often receives inquiries whether there are any general astronomical societies open to the amateur. There are several, and while they reserve the privilege of rejecting application for membership it is seldom necessary to exercise it. In most of them the amateur is made altogether welcome even if he does not yet possess much knowledge of astronomy. Among the professional personnel of astronomy there is no tendency toward loftiness or exaltation, and virtually all professionals are genuinely interested in the efforts of amateurs to break into the game; they are only too anxious, in fact, to see a more widespread interest aroused in their science and generally they willingly facilitate the admission of amateur enthusiasts to all but the purely professional associations.

The *American Astronomical Society* is frankly for professionals (though most of its members also belong to several societies made up largely of amateurs). It publishes no journal but meets twice a year in various parts of the country and the meetings, which are not large, are generally open to serious amateurs. Naturally, the subjects discussed are not elementary.

The *Royal Astronomical Society*, Burlington House, London, W. 1, England, is for professionals and advanced amateurs. There is a two guinea initiation fee and the annual dues are two guineas. A substantial publication, the *Monthly Notices*, is included. This is rather an abstruse journal. Candidates must be recommended by three members (among the members are most American professionals).

The *Royal Astronomical Society of Canada* is open to all (not necessarily Canadians) who are interested in astronomy and its *Journal* states that "more members are desired." At present there are over 600 members. Annual fee, two dollars, which includes subscription to the *Journal* (see next page); also the invaluable Observer's Handbook for the current year. (See directory.)

The *British Astronomical Association* is "open to all persons interested in astronomy," but requires that candidates be proposed either by one member or by two persons of weight and standing and from personal knowledge. Entrance fee, five shillings; annual subscription to the *Journal* (monthly) one guinea. The annual Handbook for observers is included. (See directory.)

The *Astronomical Society of the Pacific* is "open to all who feel an interest in the subject of astronomy." Annual dues, five dollars; no initiation fees. The interesting periodical is called the *Publications* (see next page) and subscription is included in the dues. While this is an amateur society, as a matter of fact most of the noted professionals on the Pacific Coast are also members because they are interested in the amateur's endeavors. This makes for close liaison between the two groups, which tend to shade more or less into one another. The amateur astronomer will discover that the same is true of astronomers almost the world over. They are democratic, interested in the popularization of their science, and generally glad to cooperate with serious-minded amateurs, many of whom have rendered astronomy valuable aid. In this country, as well as in Great Britain, Canada, France and elsewhere, various astronomical societies include both professionals and amateurs. The membership of the society just named is world-wide. (See directory.)

The *Société Astronomique de France* has more than 5,000 members in all parts of the world and is mainly composed of amateurs. Foreign membership is 30 francs a year and the publication, *L'Astronomie* (see next page) is included. For a comparatively small sum at the present exchange rate, one may also become a founding or life member. This would be an interesting way to keep up one's French throughout life; astronomical French is easy, due to the virtual identity of the scientific words. The publication is most attractively produced and illustrated. Address Secrétaire Général and enclose an international reply coupon, obtainable for five cents at any P. O. (See directory.)

PERIODICALS ON ASTRONOMY

Astronomical Journals: Most of the following are popular or semi-popular in nature. For their addresses see the Directory:

Popular Astronomy. Ten numbers a year, \$4.00 (foreign, \$4.50).

Publications of the Astronomical Society of the Pacific. Six numbers a year, \$5.00. The usual way to obtain these is to apply for membership in the Society. See previous page.

The Monthly Evening Sky Map. \$1.50 per year. More elementary than the others.

Journal of the Royal Astronomical Society of Canada. See previous page. This journal is perhaps the best suited to the needs of the beginner.

The Observatory. Published at the Royal Observatory of Greenwhich, England. Monthly. Twenty shillings a year.

L'Astronomie. Similar in scope to *Popular Astronomy.* Published by the Société Astronomique de France. See previous page.

Astrophysical Journal. Monthly. Advanced in content. \$6.00 a year.

Journal of the British Astronomical Association. Monthly. Very interesting matter for the amateur astronomer, occasionally for the practical builder. See previous page.

Revista Astronomica. Similar in scope to most of the general journals named above. Organ of the "Amigos de la Astronomia" (Buenos Aires).

Optical Journals: The Journal of the Optical Society of America, also the *Review of Scientific Instruments,* as well as the *Journal of Scientific Instruments* (the latter published in connection with the National Physical Laboratory, Teddington, Middlesex, England) should not be overlooked by serious workers in optics. Available in the larger libraries.

BOOK LIST

The following is a selected list of books described in the present volume. These (or any other books) may be obtained from the *Scientific American*, 24 West 40th Street, New York. The prices quoted *include postage in the United States and Territories*. For foreign orders add 15 cents per book to the prices given, for registration. Books are not sent on approval.

Abbot: The Sun	$ 3.70
Baker: Astronomy, An Introduction	3.20
Ball: Popular Guide to the Heavens	7.70
Barlow and Bryan: Mathematical Astronomy	2.75
Barnard: Photographic Atlas of the Milky Way	Out of print
Barns: 1001 Celestial Wonders	2.65
Barton and Barton: Guide to the Constellations	3.20
Bell: The Telescope	3.20
Campbell: Elements of Practical Astronomy	2.90
Chauvenet: Manual Sph. and Pract. Astron. (2 volumes)	10.30
Duncan: Astronomy	3.90
Eddington: The Internal Constitution of the Stars	8.70
Edser: Light for Students	2.50
Ellison: The Amateur's Telescope	2.15
Ephemeris and Nautical Almanac. Prices not uniform—1936	2.50
Fath: Elements of Astronomy	3.20
Hale: The New Heavens	1.65
Jeans: Mysterious Universe	2.40
Jeans: Universe Around Us	4.00
King: Manual of Celestial Photography	3.20
Knowlton: Physics for College Students	3.90
Martin: Friendly Stars	2.15
McKready: Beginner's Star Book	5.20
Michelson: Studies in Optics	2.65
Mitchell: Eclipses of the Sun	5.20
Mitchell and Abbot: Fundamentals of Astronomy	3.20
Moulton: Astronomy	3.90
Moulton: Introduction to Celestial Mechanics	4.20
Newton: Opticks	Out of print
Norton: Star Atlas	4.45
Olcott and Putnam: Fieldbook of the Skies	3.70
Olivier: Comets	2.50
Olivier: Meteors	5.20
Orford: Lens Work for Amateurs	1.65
Orr: Stars of the Southern Skies	1.40
Russell, Dugan and Stewart: Astronomy (2 volumes)	5.30
Shapley: Flights from Chaos	2.65
Shapley: Starlight	Out of print
Shapley and Howarth: Sourcebook in Astronomy	4.20

Smart: Textbook on Spherical Astronomy	$7.20
Southall: Mirrors, Prisms and Lenses	4.70
Splendour of the Heavens	12.50
Stetson: Manual of Laboratory Astronomy	2.40
Stetson: Man and the Stars	2.65
Stetson: Sky Map Construction for Everybody	.50
Thompson: Light, Visible and Invisible	2.90
Todd: New Astronomy	1.95
Waters: Astronomical Photography	2.15
Wood: Physical Optics	7.75

BOOKS ADDED, 1935

Men, Mirrors and Stars. By G. Edward Pendray. A popular, non-technical account of the development of astronomy and telescopes, in fascinating, readable style. The ground covered is: History of the telescope; how modern telescopes work; seeing, magnification, definition; auxiliary instruments; glass making; historic observatories; famous American telescope makers; amateur telescope makers and how (*and* how!) they have advanced the art; mirrors to come; list of world's observatories. 349 pages. Price $3.14.

The Principles of Optics. By Hardy and Perrin. Of the 618 pages of this book the first 120 are on the principles of optics—geometrical theory of image formation, aberrations, etc.—and the rest are on practical optics, with chapters on resolving power, radiation, light sources, the eye, photography, light-sensitive cells, photometry, color, optical glass, manufacture of optical parts, testing optical parts, miscellaneous optical materials, design of optical instruments, ophthalmic instruments, photographic objectives, magnifiers and oculars, telescopes, microscopes, stereoscopy, projection systems, spectroscopic apparatus, interferometers, and polarized light. None of these are treated exhaustively, as this is too broad a survey for that. Used as elementary textbook in course in optical engineering at M. I. T. Price $6.20.

Introduction to Applied Optics. By L. C. Martin, Technical Optics Dept., Imperial College of Science and Technology, London. Vol. I (319 pp.) gives elementary and general theory of optical systems, physical study of light, optical images and their defects, physiological optics, physical optics, optical glass, production and testing of lens systems, spectacles. Price $6.20. Vol. II (286 pp.): Theory and construction of instruments, telescopes (57 pp., incl. design of O. G.) microscopes, 66 pp., binocular vision and instruments, photo. lenses, testing opt. instruments. Largely mathematical, though math is elementary. Occupy position between the elementary Hardy and Perrin and advanced Conrady book. Price $6.20. Volumes are obtainable separately.

The Home-made Telescope. By W. F. Decker. Instructions for making a six-inch (spherical) mirror and a substantial wooden-tube, pipe fitting mounting. About suitable for age 14–16. A neat booklet. Price $.60.

The Moon, an atlas, by Walter Goodacre, F.R.A.S. A 77-inch map of the moon cut into 25 sections, each with an accompanying section of drawings and descriptions of lunar formations. 364 pp. 8″ x 10″. Price $5.25.

NOTES

KITS OF MATERIAL FOR MIRROR MAKING: These consist of a glass disk for the mirror, glass tool of equal diameter, the necessary abrasives, coarse and fine (several sizes), including rouge, and are furnished in cartons, ready for beginning work, by several dealers in telescope makers' supplies. See their statements in the *Scientific American.* (To assist those of the more distant purchasers of this book who may lack access to copies of the *Scientific American,* and who would therefore be greatly delayed in obtaining the addresses from that source, the publishers will endeavor, on request, to notify some or all of the dealers that price lists of beginner's kits are desired—provided these requests come from *without* the North American continent. Most of the same dealers supply prisms, eyepieces and other accessories.

MATERIALS

No pretense is made that the following list is complete. The addresses of the firms named may be found in the Directory.

Quartz, fused: General Elec. Co., Attention W. H. Jones, Schenectady Works.

Brass Tubing: Patterson Bros.; Besley and Co.

Lamp, small, for Knife-edge Test: Vapo-Cresoline Co. (40 cents, postpaid).

Carborundum: The Carborundum Co.

Telescopes, second hand: Telescope Mart, 9 Vincent St., Cambridge, Mass.

Finishing abrasives: Bausch and Lomb; American Optical Co.; The Norton Co.

Chance Brothers Optical Glass: Donald Sharp (Bailey and Sharp), American Agent.

Pyrex: Corning Glass Works.

Rouge: For fast work, Am. Opt. Co.; for fine finishing, Bausch and Lomb.

Crushed Steel: Pittsburgh Crushed Steel Co.

Stellite: Haynes Stellite Co.

H C F: Root, A. I. Co.; Dadant and Sons; Sears, Roebuck & Co.; Montgomery Ward & Co.

Schott-Jena Optical Glass: Fish-Schurman Corp., exclusive U. S. agents.

Invar: Crucible Steel Co. of America; Holcomb Steel Co.; Simonds Saw and Steel Co.

Lacquer: Egyptian Lacquer Mfg. Co.

Replica Gratings: Central Scientific Supply Co.

Magnetic black rouge: Binney & Smith.

DIRECTORY

To facilitate ready access to institutions and individuals mentioned in the text, and to promote direct intercourse between amateurs, many of the addresses are here placed before the reader. It must be remembered that as time elapses some of these addresses will become obsolete.

Aluminum Company of America, 2456 Oliver Bldg., Pittsburgh, Pa.
American Association of Variable Star Observers, Leon Campbell, Harvard College Observatory, Cambridge, Mass.
American Meteor Society, Care of Professor Charles P. Olivier, Director Flower Observatory, University of Pennsylvania, Philadelphia, Pa.
American Optical Co., Southbridge, Mass.
Astronomical Society of the Pacific, C. H. Adams, secretary, 803 Merchants' Exchange Bldg., San Francisco, Calif.
Astrophysical Journal, 5750 Ellis Ave., Chicago, Ill.
Bailey, Dr. H. Page, Riverside, Calif.
Bailey and Sharp, Hamburg, N. Y.
Bakelite Corp., 247 Park Ave., New York.
Baker, J. T. Chem. Co., North Phillipsburg, Pa.
Bausch and Lomb Optical Co., Rochester, N. Y.
Beck, R. and J., Ltd., 68 Cornhill, London, E.C. 4, England.
Besley & Co., Chas. H., 118 North Clinton St., Chicago, Ill.
Binney and Smith, 41 East 42nd St., New York.
Boston Gear Works, North Quincy, Mass.
British Astronomical Association, 48 Basildene Road, Hounslow West, London, England.
Brookings, Ernest, Care of Jones and Lamson Machine Co., Springfield, Vt.
Bureau of Standards, U. S., Washington, D. C.
Carborundum Company, Niagara Falls, N. Y.
Carpenter, Prof. Arthur Howe, 811 Bell Ave., La Grange, Ill.
Central Scientific Supply Co., 460 East Ohio St., Chicago, Ill.
Chance Brothers, Birmingham, England. (See Sharp, Donald.)
Cooke, T. and Sons, Ltd., York, England.
Cooke, Troughton and Simms, Ltd., York, England (successors to above).
Corning Glass Works, Corning, N. Y.
Croston, George, La Grande, Wash.
Crucible Steel Co. of America, 17 East 42nd St., New York.
Cutler, Rev. Harold N., 7 Becher Ave., Rochelle Park, N. J.
Dadant and Sons, Hamilton, Ill.
Dall, Horace E., 166 Stockingstone Road, Luton, Beds., England.
Eastern Science Supply Co., Box 1414, Boston, Mass.
Egyptian Lacquer Mfg. Co., 90 West St., New York.
Eimer and Amend, 3rd Ave. and 18th St., New York.
Ellison, Rev. W. F. A., Director Armagh Observatory, Armagh, Northern Ireland.

English Mechanics, 2 Bream's Buildings, Chancery Lane, London, E.C. 4, England.
Everest, A. W., 15 Allengate Ave., Pittsfield, Mass.
Fecker, J. W., 2016 Perrysville Ave., Pittsburgh, Pa.
Fish-Schurman Corp., 230 E. 45th St., New York.
Gaertner Scientific Corp., 1201 Wrightwood Ave., Chicago, Ill.
Garrison, Jack, 802 Hamilton Ave., Indianapolis, Ind.
General Electric Co., 1 River Road, Schenectady, N. Y.
General Electric Review, Schenectady, N. Y.
General Electric Vapor Lamp Co., Hoboken, N. J.
Glass Industry, 233 Broadway, New York.
Goodacre, Walter, Warratah 125, Holden Road, Worth Finchley, London, N. 12, England.
Government Printing Office, Washington, D. C.
Hamilton, Professor George H., "Iona," Mandeville, Jamaica, B.W.I.
Hargreaves, F. J., Mirastelle, Woodland Way, Kingswood, Surrey, England.
Haynes Stellite Co., Kokomo, Ind.
Hilger, Adam, Ltd., 24 Rochester Place, Camden Road, London, N.W. 1, England.
Hindle, John H., Director, Union Engineering Works, Cartniel St., Witton, Blackburn, Lancs., England.
Holcomb Steel Co., 1 Dominick Street, New York.
Ingalls, Albert G., Telescope Editor, the Scientific American, 24 West 40th St., New York.
Journal of the Franklin Institute, Franklin Institute Museum, Philadelphia, Pa.
Journal Opt. Soc. of Am., The American Institute of Physics, 11 East 38th St., New York.
Journal of the Royal Astronomical Society of Canada, 198 College St., Toronto, Ont.
Journal of Scientific Instruments, Cambridge University Press, Fetter Lane, London, E.C. 4, England.
Journal of the Society of Glass Technology, Sheffield, England.
Keil, Ernst, 105 S. Catalina Ave., Pasadena, Calif.
Kirkham, Alan R., 3801 S. 31st St., Tacoma, Wash.
L'Astronomie (see Société Astronomique de France).
Lee, John C., Grove St., Wellesley, Mass.
Lower, Harold A., 1032 Pennsylvania St., San Diego, Calif.
Lutz, G. L., 323 Collins Ave., Moorestown, N. J.
Mayall, R. N. and M. W., Harvard College Observatory, Cambridge, Mass.
Monthly Evening Sky Map, 367 Fulton St., Brooklyn, N. Y.
Mt. Wilson Observatory, Pasadena, Calif.
Norton Co., Worchester, Mass.
Nature, Macmillan & Co., Ltd., St. Martin's St., London, W.C. 2, England.
Noblitt, Loren S., Alma College, Alma, Mich.
Observatory, The (see Royal Observatory of Greenwich).

Optical Society, 1 Lowther Gardens, Exhibition Road, South Kensington, London, S.W. 7, England.
Patterson Bros., 27 Park Row, New York, N. Y.
Pickering, David B., 171 S. Burnett St., East Orange, N. J.
Pierce, John M., 11 Harvard St., Springfield, Vt.
Pittsburgh Crushed Steel Co., A. V. R. R. and 61 St., Pittsburgh, Pa.
Pittsburgh Plate Glass Co., Grant Bldg., Pittsburgh, Pa.
Popular Astronomy, Carleton College, Northfield, Minn.
Porter, Russell W., Astrophysical Observatory, The California Institute of Technology, 1201 East California St., Pasadena, Calif.
Product Engineering, 330 West 42nd St., New York.
Review of Scientific Instruments, The American Institute of Physics, 11 East 38th St., New York.
Revista Astronomica, Calle Sarmiento 299, Escritorio 299, Buenos Aires, Argentina.
Root, A. I., Co., Medina, Ohio.
Royal Astronomical Society, Burlington House, London, W. 1, England.
Royal Astronomical Society of Canada, 198 College St., Toronto, Ontario, Canada.
Royal Observatory of Greenwich, London, S.E. 10, England.
St. Clair, B. W., Director Standardizing Laboratory, General Electric Co., West Lynn, Mass.
Saint-Gobain, Chauney et Cirey, 1 bis, Place des Suassaies, Paris (VIIIe), France.
Scientific American, 24 West 40th Street, New York.
Sellers, F. J., 42 Church Crescent, London, N. 10, England.
Sharp, Donald, agent for Chance Brothers, Hamburg, N. Y.
Simonds Saw & Steel Co., Lockport, N. Y.
Société Astronomique de France, Madame Camille Flammarion, Secrétaire-Général, Observatoire de Juvisy, Seine-et-Oise, France.
Thomson, Professor Elihu, Director Thomson Research Laboratory, West Lynn, Mass.
U. S. Gypsum Co., 300 W. Adams St., Chicago, Ill.
Vapo-Cresoline Co., 62 Cortlandt St., New York.
Ward's Natural Science Establishment, Rochester, N. Y.
Webster, J. Milo, Wyomissing, Pa.
Welch, W. M., Scientific Co., 1516 Orleans St., Chicago, Ill.
Wilson, H. W., Co., 958 University Ave., New York.
Wilson, Latimer, 1405 Gartland Ave., Nashville, Tenn.
Wright, Franklin B., 155 Bret Harte Road, Berkeley, Calif.
Yalden, J. Ernest G., 120 Woodridge Place, Leonia, N. J.
Yerkes Observatory, Williams Bay, Wisc.
Zeiss, Carl, Inc., 485 Fifth Avenue, New York, (Jena, Germany).

CLUBS

The following are the clubs of amateur telescope makers, at date of compilation.

Telescope Makers of Springfield, R. J. Lyon, Sec., 252 Summer St., Springfield, Vt.

Astronomical Society of the Stanley Club, A. W. Everest, President, 15 Allengate Ave., Pittsfield, Mass.

Academy of Science and Art of Pittsburgh, Astronomical Section, Leo J. Scanlon, Pres., 1405 East St., Pittsburgh, Pa.

Amateur Telescopist's Association, East End, Pittsburgh, Nelson A. Mowry, Sec., 809 Garland St., Edgewood, Pittsburgh 18, Pa.

Eastbay Astronomical Association, Telescope Makers' Section, Franklin B. Wright, Chairman, 155 Bret Harte Road, Berkeley, Calif.

Amateur Telescope Makers of San Francisco, Frank J. Corrigan, Sec., 1259 18th Ave., San Francisco, Calif.

Amateur Telescope Makers of Berkeley, Dr. W. T. Bush, American Trust Bldg., Berkeley, Calif.

Amateur Telescope Makers of the Golden Gate, a federation of the San Francisco and Berkeley clubs named above, with Oakland and other Bay cities clubs.

Amateur Telescope Makers of Chicago, William Callum, Sec., 1319 West 78 Street, Chicago, Ill.

Amateur Telescope Makers of Gray's Harbor, C. H. Rose, Sec., Aberdeen, Wash.

Amateur Telescope Makers of Cincinnati, W. Clemmer Mitchell, Sec., 2390 Wheeler Street, Cincinnati, Ohio.

Dallas Astronomical Society, Chester A. Howard, 3120 Princeton Ave., Dallas, Tex.

Amateur Telescope Makers of Indianapolis, V. E. Maier, Sec., 1306 Parker Ave., Indianapolis, Ind.

Amateur Telescope Makers of New Orleans, Harry L. Lawton, 215 Stella St., New Orleans, La.

Amateur Astronomical Society of Los Angeles, Inc., George J. Bartlett, Sec., 2606 West 8th St., Los Angeles, Calif.

Amateur Telescope Makers and Astronomers of Tacoma, George Croston, Sec., LaGrande, Wash.

Amateur Telescope Makers of Buffalo, Thaddeus Czerniejewski, Chairman, 113 Franklin St., Lackawanna, N. Y.

Amateur Telescope Makers of Dayton, William Braun, Sec., 115 Bolton Ave., Dayton, Ohio.

Skyscrapers Amateur Astronomical Society of Rhode Island, Rev. J. G. Crawford, Sec., Saunderstown, R. I.

Detroit Amateur Astronomical Society, Howard Morehouse, 4336 Dickerson Ave., Detroit, Mich.

Milwaukee Astronomical Society, L. W. Armfield, Sec., 2066 S. 59 St., Milwaukee, Wisc.

Amateur Telescope Makers of Boston, Wagn. H. Hargbol, Pres., 600 Beech St., Roslindale, Mass.

Amateur Telescope Makers of Lorain, Wm. A. Mason, 1305 Lakeview Ave., Lorain, Ohio.

Amateur Telescope Makers of Kansas City, Dana V. Bidwell, Sec., 5525 Woodland Ave., Kansas City, Mo.

Citrus Belt Astronomers, H. Page Bailey, 3724 Franklin Ave., Riverside, Calif.

Astronomers' Guild of Jamestown, J. Elwood Johnson, Pres., 28 S. Main St., Jamestown, N. Y.

Burbank Telescope Club, Burbank, Calif.

Rochester Astronomy Club, Prof. F. C. Fairbanks, University of Rochester, Rochester, N. Y.

Amateur Astronomical Association, Joseph A. McCarroll, Pres., 521 Palisade Ave., Teaneck, N. J.

Case Astronomical Club, Kenyon Zapf, The Case School of Applied Science, Cleveland, Ohio.

Amateur Telescope Makers of Cleveland, R. A. Gordon, Sec., 1539 Union Trust Bldg., Cleveland, Ohio.

Tri-City Astronomical Club, Bernhard Nordblom, Jr., Secretary, 929 Grand Ave., Davenport, Ia.

Northeast Michigan Telescope Club, Dr. C. L. Hess, 308 Davidson Bldg., Bay City, Mich.

Telescope Makers' Section, Amateur Astronomer's Association, Ramiro Quesada, leader, American Museum of Natural History, New York, N. Y.

Amateur Telescope Makers of New York, Lew Lojas, 1510 White Plains Road, The Bronx, New York, N. Y.

BIOGRAPHICAL

A glimpse of human interest concerning the two principal authors of this book may prove to be of interest to the reader.

Russell Williams Porter, author of Part I, and the general adviser, source of inspiration and collaborator with the editor in the preparation of the entire book—very largely, also, its illustrator—has had a romantic career; so much so that the writers of human interest articles for the magazines have not missed him (*e.g.*, "One Happy Man," by Webb Waldron, *The American Magazine,* Nov. 1931). He was born in 1871. As a youth he studied architecture at the Massachusetts Institute of Technology and, while still an undergraduate, became enamored of arctic exploration, through the direct influence of Admiral Peary. He paid most of his college expenses from the proceeds of summer excursions to the Far North which he organized and on which he conducted other students eager for adventure. For many years thereafter he devoted his life to arctic exploration, making eight extended trips north of the Arctic Circle with Peary, Fiala and others, acting on these expeditions in the capacity of artist, astronomer, surveyor, topographer and museum collector, in Greenland, Baffin Land, Alaska and Franz Josef Land. Turning from these pursuits he became interested in telescope making, wholly as an amateur and very much as the general readers of the present volume have become interested. When the United States entered the World War he turned the skill thus gained to the advantage of the government, doing optical work throughout the war period at the National Bureau of Standards in Washington. Later he returned to Springfield, Vermont, his birthplace, as Optical Associate with the Jones and Lamson Machine Co., well known in the machine tool industry the world over, and there he developed the screw-thread optical comparator originally conceived by Governor James Hartness, head of that industry. As a side line he also built fifty "garden" telescopes, each with a six-inch mirror, which embodied in pleasing form for the amateur user his invention of the split ring equatorial mounting (page 349). Discovering intelligent interest in amateur optics and astronomy among the expert mechanics in the Vermont community, in 1921 he organized the "Telescope Makers of Springfield." Through this and numerous other activities in practical optics, he became known to the principals who are building the world's largest telescope in California and was offered an opportunity to collaborate with them in the design and construction of that giant instrument—the largest "amateur's telescope" of all. Amateur telescope makers in this country rightly regard Russell W. Porter as the father of their hobby. [See also "Who's Who in America."]

The Rev. William Frederick Archdall Ellison, around whose detailed, explicit instructions for mirror making and objective lens making (Part II) the present volume is organized, was born in 1864 and was formerly the Rector of Tintern. Since 1918, however, he has been Director of the astronomi-

cal observatory at Armagh, in Northern Ireland. He first engaged in telescope making purely as an amateur, but the world, on discovering the excellence of his handiwork, soon trod the traditional beaten path to his doorstep to obtain his mirrors and these are in the hands of many users in different lands. On the occasion of a brief visit to Armagh in 1928, the writer of the present notes found this tall man of heavy frame—a striking figure—dressed in the habiliments of the clergy, with the leggings and low, broad, black felt hat of the Church of Ireland, which corresponds to the Church of England. A photograph obtained on the request of the Scientific American has been inserted by the editor in Part II, and an informal snapshot appears on page 861. The Rev. Mr. Ellison is also an expert organist and, on the occasion mentioned, his performance on the great electric organ of the Armagh Cathedral proved quite equal in quality with his performances on optical surfaces. He is a tennis player. So many amateur telescope makers have inquired concerning his nationality ("Is he an Irishman?") that the matter was once hinted at in a letter. This is the reply received: "Re. 'Irishman,' I am that, to the extent of being born in Ireland. I am to that same extent a Kilkenny cat, for I was born in that famous county. But my father was of Scotch extraction and my mother of English, so make what you can of it." [See also "Who's Who" (Great Britain).]

NOTES

NOTES

A LAST WORD TO BEGINNERS

The beginner's "Public Enemy No. 1," the evident cause of more grief and disappointment than any other factor in his endeavors, has been insufficient grinding, mainly at the middle stages, despite the warning on pages 351–354, first published in an earlier edition. Literally hundreds have written appeals about like the following: "I have now been polishing my mirror for more than 20 hours, and am at last beginning to wonder whether it will be worth while to go on. There remain two or three big pits per square inch, which I could not seem to see until I had polished for several hours and cleared away the many smaller pits that for a time must have camouflaged them. Only then did I realize that the pits I am now trying to polish out are very considerably deeper than the others. The longer I polish, the more reluctant I feel about making a return to grinding. On the other hand, if I don't return to grinding, there appears to be little prospect of finishing short of another 20, 30 or 40 hours. Must I give up and go back?" If the extra and unnecessary time spent could be totalled, represented by all such cases that have occurred up to 1935 when the present note was inserted in a later edition of this book, the sum would reach a probable 50,000 man-hours. Many have polished 10, 20, 30, or even 50, extra hours on isolated deep pits. It is in the hope of enabling the beginner from the start to avoid falling into such a trap, that the present note is now (fourth edition) added to this book as the last word.

It is not alone the very beginner, working on his first job, who finds himself in a dilemma like this. Until the lesson has soaked in well, through repetition of the same tragedy perhaps twice or even three times, a worker is likely to find himself in almost as bad a fix right over again. On the second occasion he may even have taken previous pains to make a prolonged search, and studied the mirror with a microscope under both low powers and high, after each stage of grinding, and concluded that "this time, anyway, there are no big pits—they absolutely aren't there." So he begins polishing the mirror. After about four hours, the finer pits being by then cleared away, there in front of his eyes stand the same damned pits again, thumbing their noses at him. Where did they come from?

The catch is this: It is difficult or impossible to decide positively, after examining a surface in strong light or under a microscope, whether large pits are hiding out in the confusing complex then seen. Such a surface is most deceptive. The pits do not stand out in the form of neat, round, isolated craters of different sizes, as they will after the rounded spaces between them have been leveled off by polishing for an hour or so. Instead, what is seen is a tangled microscopic landscape—folds, creases, ridges, knolls, and whatnot, all jumbled together, like the relief map of a New England state. Therefore most old hands, having "been there" themselves in their own time, no longer try to judge when the pits of a previous stage of grinding have been wiped off entirely and replaced by those of the next finer stage. Instead, they simply give each stage one full hour of grinding—60 minutes of actual elbow grease. (The first stage, of course, is roughing out and need not be

timed at all; it will come to whatever it comes to.) Particularly should this be done on Pyrex, which is much harder than plate glass.

This doubling of the half hour (six five-minute wets) suggested by Ellison on page 79 is definitely not an expedient to offset the very beginner's inexperience. It is true, Ellison, a very experienced hand, can reduce the hour's time; though Everest, who had made and mothered some 150 optical surfaces up to 1935, does not find it worth while to try.

Six wets of the finer sizes of Carbo will come to about half an hour, as already stated, but the coarser sizes break down so rapidly that six wets of these would equal hardly more than 15 minutes, unless each wet were dragged out past the point where the reduced abrasion from the broken up grains was worth the abrasive saved. So it may be best to measure the work by the clock.

This recommendation—one hour per stage—apparently means more work. But does it? Are not six hours of grinding and ten hours of polishing (on pitch without prepolishing, otherwise less) a whole lot better than three hours of grinding and 20 or 30 hours of polishing, or even more?

If in spite of precaution the beginner does find himself in such a jam—that is, deep pits after about 10 hours' polishing—the ideal thing is, of course, to go back to grinding. The return in most cases should not be merely to the final stage of grinding but to about the third stage. This is because the offending pits are not last stage pits; if they were, the long period of polishing already given the glass would have removed them. Instead, they are probably the bottom halves or two-third portions of first or second stage pits, and even quite a long time spent with No. 600 on these coarser pits will hardly whip them, at least as economically of time as a succession of about the three final stages. This may be looked at in a quantitative sense, thus: Pits are about proportional in depth to the size of the grains that make them. The grain diameters of the Carbo series 60, 120, 220, 280, 400 and 600, as given by the manufacturer, are in the following proportion: 1170, 490, 290, 156, 81, 42 (stated in 100,000ths of an inch); M 303½ on the same scale is 16, Levigated Alumina 4, rouge 2—these as measured by S. H. Sheib of Richmond. These figures tell the whole story and should be studied closely. If whipping the 1170- or 490-sized pits with a 2-sized abrasive requires 20 or 30 hours' work, will even a 42-sized abrasive, used alone, be likely to whip them as economically of time as 290-, 156-, 81- and 42-sized abrasives used in logical sequence?

The above argument also shows the inadvisability of believing that "a few extra wets on the final stage will clear the slate," as has sometimes been advised in cases where there has not been good grinding at earlier stages. It most likely won't. Instead, this bit of bad advice may cause the beginner to be less careful in the earlier stages than he otherwise would, serene in the belief that everything will come out all right in the end if he only gives the job some extra licks on the last stage. Or he may believe that, as the ever-optimistic Mr. Micawber said, "something will turn up." Something will. Pits.

But if, in spite of all, you do find yourself in such a fix after 10 hours of

polishing, a practical thing to do, considering that counsels of perfection may mean entire discouragement to the beginner and therefore be self-defeating, is to go ahead and figure the mirror as it is, put it in use, and thus have it to enjoy while a better mirror is made. The pits will not very greatly affect its working value—at least the beginning observer is quite unlikely even to know that anything is very wrong; and, for that matter, even a case-hardened telescope user would find it hard to put a finger on the exact optical harm done by a few stray pits. There are, however, but few who would deliberately recommend leaving pits on a mirror—this merely on general principles of good housekeeping: pits are the bedbugs of optics. And then covenant with yourself either to go back later and properly grind and polish that pitted mirror, or else follow the advice on page 287, just above the picture.

Good luck!

The Ed., by request

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